Investigating magnetic fluctuations in gyrokinetic simulations of tokamak SOL turbulence

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PPPL Theory Research & Review Seminar
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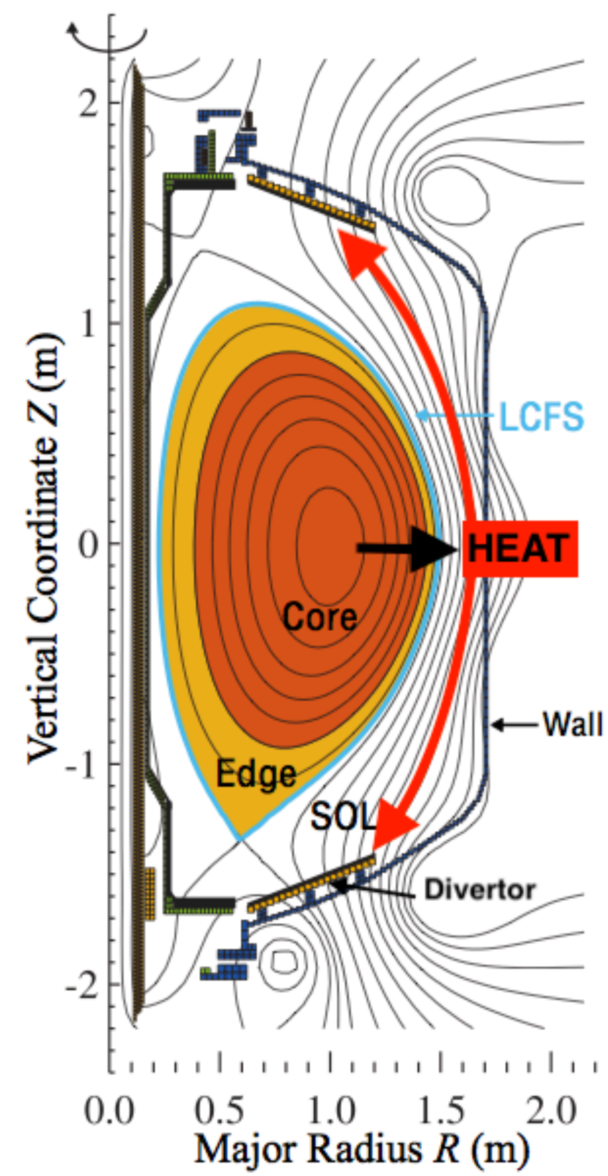
Why is SOL turbulence important?

- Plasma properties in the tokamak edge/ scrape-off layer (SOL) constrain component lifetime and reactor performance

- Heat exhausted in SOL could damage divertor plates if heat flux width is too narrow
  - Can SOL turbulence broaden the heat flux width?
  - Can electromagnetic effects be important for SOL turbulence?



Modeling the edge/SOL is challenging

- Gyrokinetic (GK) theory and simulation are important first-principles tools for studying turbulence and transport in fusion plasmas, but most present codes optimized for core, small fluctuations (delta-f)
- Edge/SOL more challenging: large-amplitude fluctuations, open field lines, plasma-wall interactions, X-point geometry, atomic physics, transition from kinetic to fluid regimes → need specialized full-f GK codes
- Including electromagnetic effects (allowing magnetic field to fluctuate) also challenging → all GK SOL results to-date have been electrostatic (no magnetic fluctuations)
- Several GK codes making great progress in edge/SOL
  - XGC1, COGENT, ELMFIRE, GENE, Gkeyll, etc
- Essential to have several independent codes to attack from different perspective and cross-check on difficult turbulence problems!

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Methods for solving gyrokinetic system

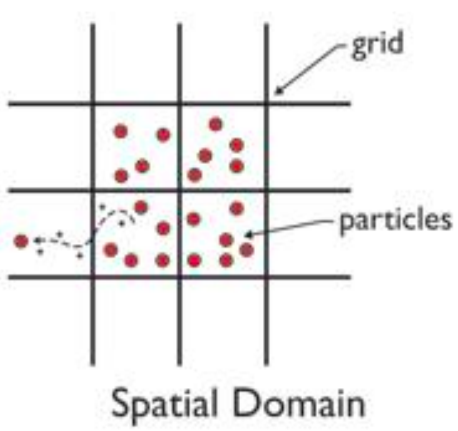
Particle-in-cell (Lagrangian)

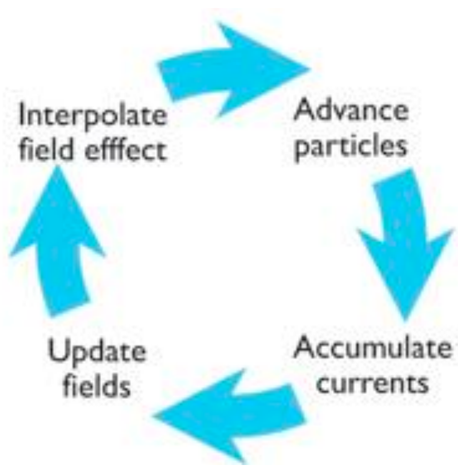
Continuum (Eulerian)

Methods for solving gyrokinetic system

Particle-in-cell (Lagrangian)

- Sample phase space with ensemble of N_p 'superparticles'
- Fields on 3D grid, particles move through grid
- Historically, EM fluctuations challenging in GK PIC codes due to numerical "Ampere cancellation" problem
  - Codes like ORB5 and XGC1 have made good recent progress to mitigate issue





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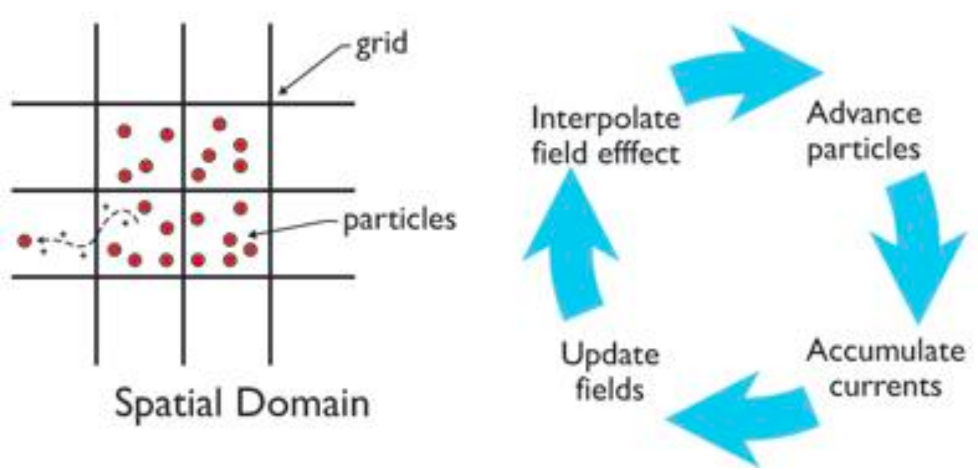
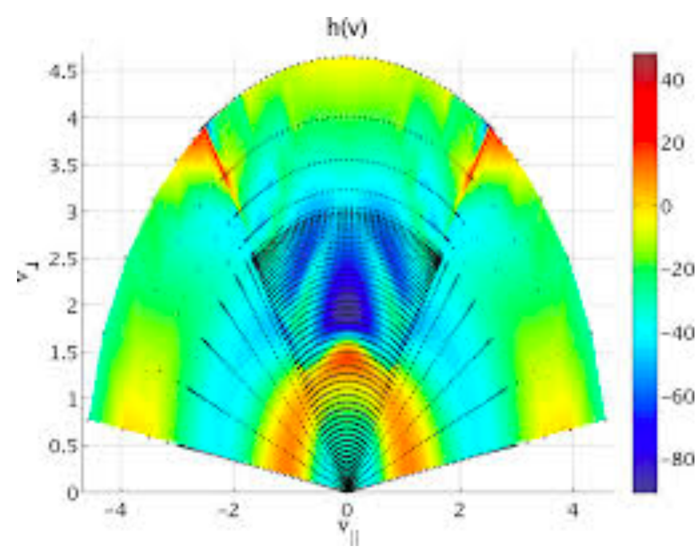


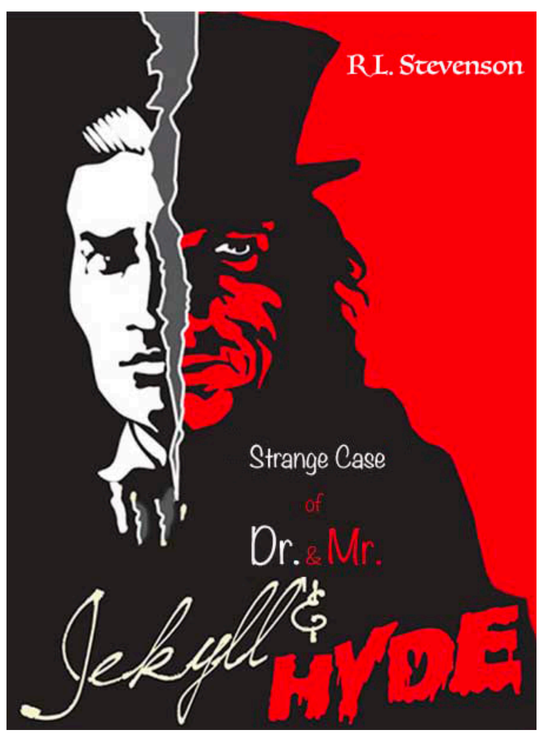
Continuum (Eulerian)

- Discretize distribution function $f(x, y, z, v_{||}, \mu)$ on 5D phase space grid
- Can solve with standard PDE methods, e.g. spectral, finite volume, discontinuous Galerkin, etc.
- Continuum electromagnetic GK codes have mostly avoided the Ampere cancellation problem



Barnes et al, 2010

Methods for solving gyrokinetic system



https://github.com/ammarhakim/gkyl/

https://gkeyll.readthedocs.io

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Gkeyll

- First successful continuum GK code on open field lines
- **First electromagnetic GK on open field lines**

Full-f electromagnetic gyrokinetics

EMGK equation, $f_s = f_s(\boldsymbol{R}, v_\parallel, \mu; t)$

$$\frac{\partial f_s}{\partial t} + \dot{\boldsymbol{R}} \cdot \nabla f_s + \dot{v}_\parallel \frac{\partial f_s}{\partial v_\parallel} = C[f_s] + S_s$$

with nonlinear phase-space trajectories

$$\dot{\boldsymbol{R}} = \{\boldsymbol{R}, H_s\} = \frac{\boldsymbol{B}_\mathbf{0}^* + \delta \boldsymbol{B}_\perp}{B_\parallel^*} v_\parallel + \frac{\hat{\mathbf{b}}}{q_s B_\parallel^*} \times (\mu \nabla B + q_s \nabla \phi)$$

$$\dot{v}_\parallel = \{v_\parallel, H_s\} - \frac{q_s}{m_s}\frac{\partial A_\parallel}{\partial t} = -\frac{\boldsymbol{B}_\mathbf{0}^* + \delta \boldsymbol{B}_\perp}{m_s B_\parallel^*} \cdot (\mu \nabla B + q_s \nabla \phi) - \frac{q_s}{m_s}\frac{\partial A_\parallel}{\partial t}$$

where $\boldsymbol{B}_\mathbf{0}^* = \boldsymbol{B}_\mathbf{0} + (m_s v_\parallel / q_s) \nabla \times \hat{\mathbf{b}}$ and $\delta \boldsymbol{B}_\perp = \nabla A_\parallel \times \hat{\mathbf{b}}$.

- No assumption of scale separation between background and fluctuations
- Taking long-wavelength (drift-kinetic) limit, neglecting gyroaveraging for now
- Using symplectic ($v_\parallel$) formulation of EMGK, so $\frac{\partial A_\parallel}{\partial t}$ appears explicitly

Full-f electromagnetic gyrokinetics

Quasineutrality equation (long-wavelength):

$$-\nabla \cdot \sum_s \frac{m_s n_{0s}}{B^2} \nabla_\perp \phi = \sum_s q_s \int d^3v \; f_s \tag{1}$$

Parallel Ampère equation:

$$-\nabla_\perp^2 A_\parallel = \mu_0 \sum_s q_s \int d^3v \; v_\parallel f_s \tag{2}$$

Can take $\frac{\partial}{\partial t}$ to get an exact Ohm's law:

$$-\nabla_\perp^2 \frac{\partial A_\parallel}{\partial t} = \mu_0 \sum_s q_s \int d^3v \; v_\parallel \frac{\partial f_s}{\partial t} \tag{3}$$

Writing GK eq. as

$$\frac{\partial f_s}{\partial t} = \frac{\partial f_s}{\partial t}^\star + \frac{q_s}{m_s} \frac{\partial A_\parallel}{\partial t} \frac{\partial f_s}{\partial v_\parallel}, \tag{4}$$

where $\frac{\partial f_s}{\partial t}^\star$ denotes all the terms in the gyrokinetic equation except the $\frac{\partial A_\parallel}{\partial t}$ term, can write Ohm's law as

$$\left(-\nabla_\perp^2 + \sum_s \frac{\mu_0 q_s^2}{m_s} \int d^3v \; f_s \right) \frac{\partial A_\parallel}{\partial t} = \mu_0 \sum_s q_s \int d^3v \; v_\parallel \frac{\partial f_s}{\partial t}^\star \tag{5}$$

Ampère cancellation problem

- In $p_{\|}$ formulation, Ampère's law:

$$\left(-\nabla_\perp^2 + C_n \sum_s \frac{\mu_0 q_s}{m_s} \int d^3p \; f\right) A_\| = C_j \; \mu_0 \sum_s \frac{q_s}{m_s^2} \int d^3p \; p_\| f$$

- "Cancellation problem" arises when there are small errors in the calculation of the integrals, represented by C_n and C_j (which should be exactly 1 in the exact system)

- Recall $v_\|$ formulation Ohm's law... same problem...

$$\left(-\nabla_\perp^2 + C_n \sum_s \frac{\mu_0 q_s^2}{m_s} \int d^3v \; f_s\right) \frac{\partial A_\|}{\partial t} = C_j \; \mu_0 \sum_s q_s \int d^3v \; v_\| \frac{\partial f_s}{\partial t}^\star$$

- The simplest Alfvén wave dispersion relation (slab geometry, uniform Maxwellian background with stationary ions) becomes (with $\hat{\beta} \equiv \frac{\beta_e}{2}\frac{m_i}{m_e}$)

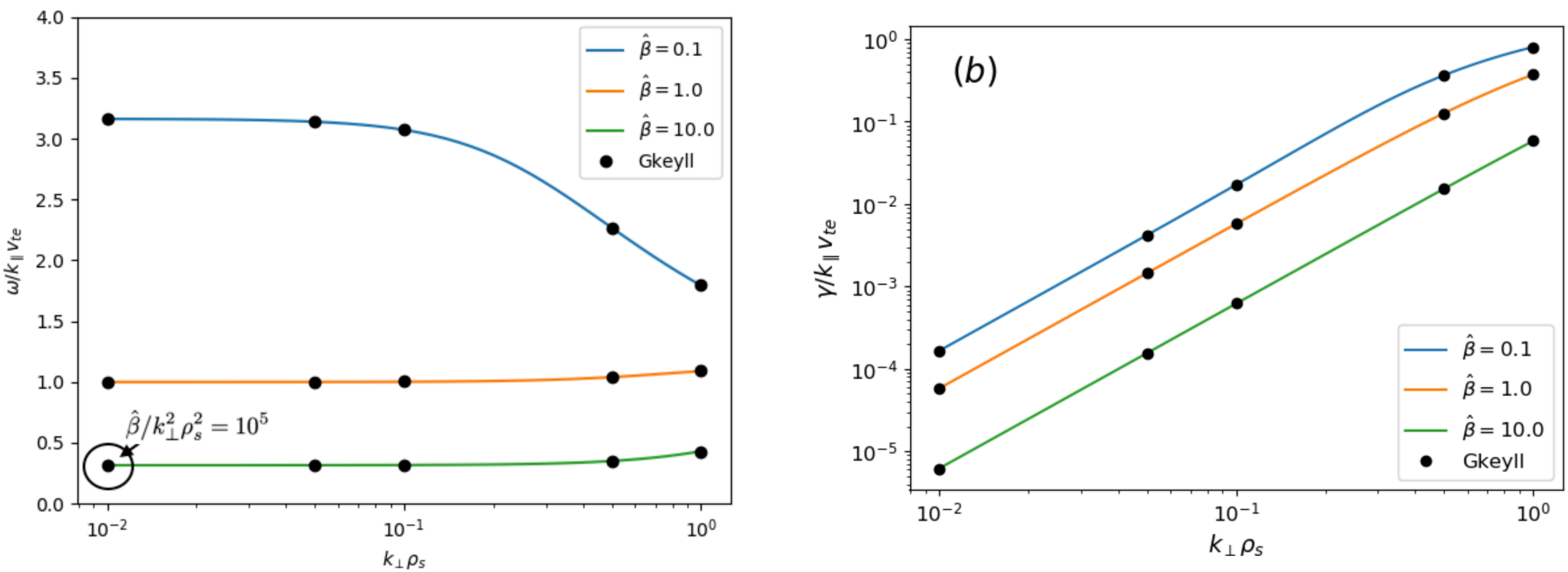
$$\omega^2 = \frac{k_\|^2 v_A^2}{C_n + k_\perp^2 \rho_s^2 / \hat{\beta}} \left[1 + (C_n - C_j) \frac{\hat{\beta}}{k_\perp^2 \rho_s^2}\right]$$

- This reduces to the correct result if integrals calculated consistently, so that $C_n = C_j$, but if not there will be errors $\sim \omega_H$ for modes with $\hat{\beta}/k_\perp^2 \rho_s^2 \gg 1$.

Gkeyll's DG scheme computes integrals consistently so that errors cancel exactly (appendix of Mandell et al, JPP 2020 shows numerical dispersion relation calculation)

Linear benchmark: kinetic Alfvén wave

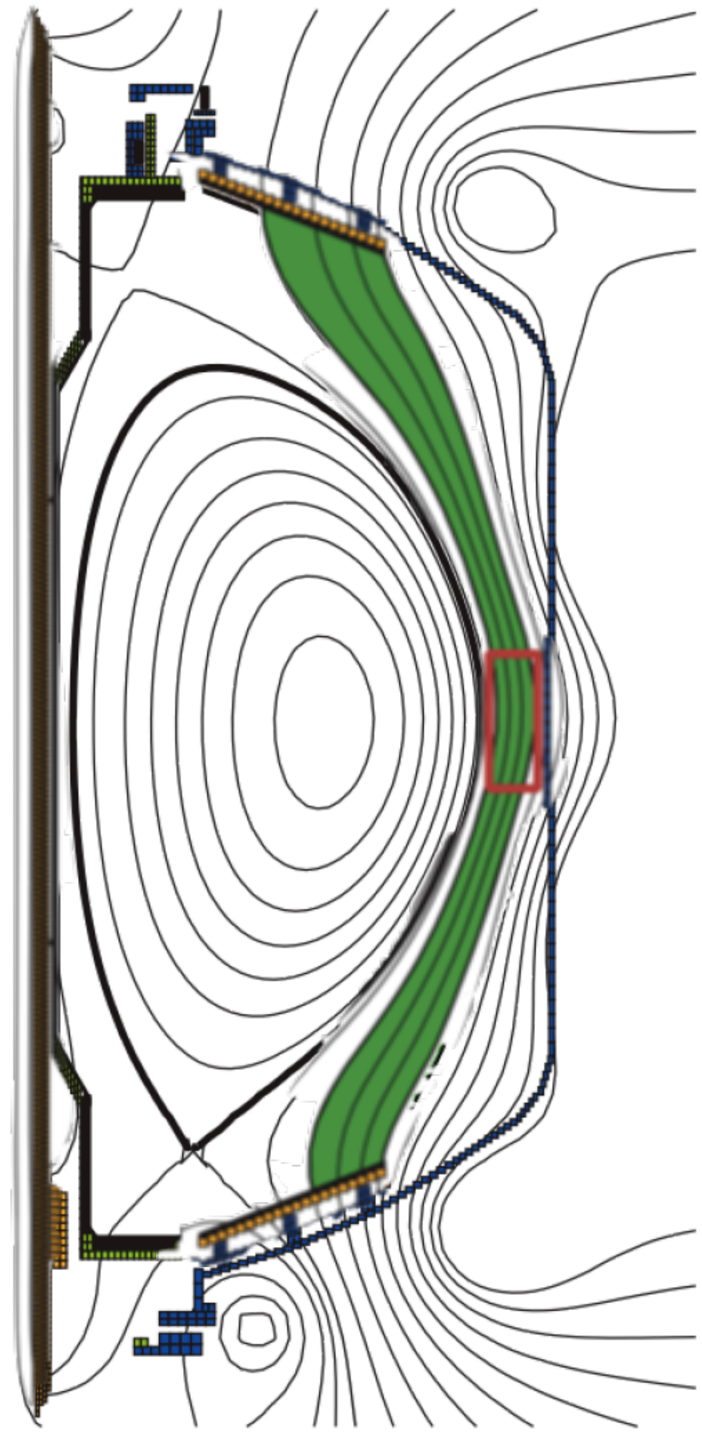
$$\omega^2 = \frac{k_\parallel^2 v_A^2}{C_n + k_\perp^2 \rho_s^2/\hat{\beta}} \left[1 + (C_n - C_j)\frac{\hat{\beta}}{k_\perp^2 \rho_s^2} \right] \qquad (k_\perp \rho_s \ll 1)$$



Gkeyll results match theory very well, even for case with $\dfrac{\hat{\beta}}{k_\perp^2 \rho_s^2} = \dfrac{\beta_e/2}{k_\perp^2 \rho_s^2}\dfrac{m_i}{m_e} = 10^5$

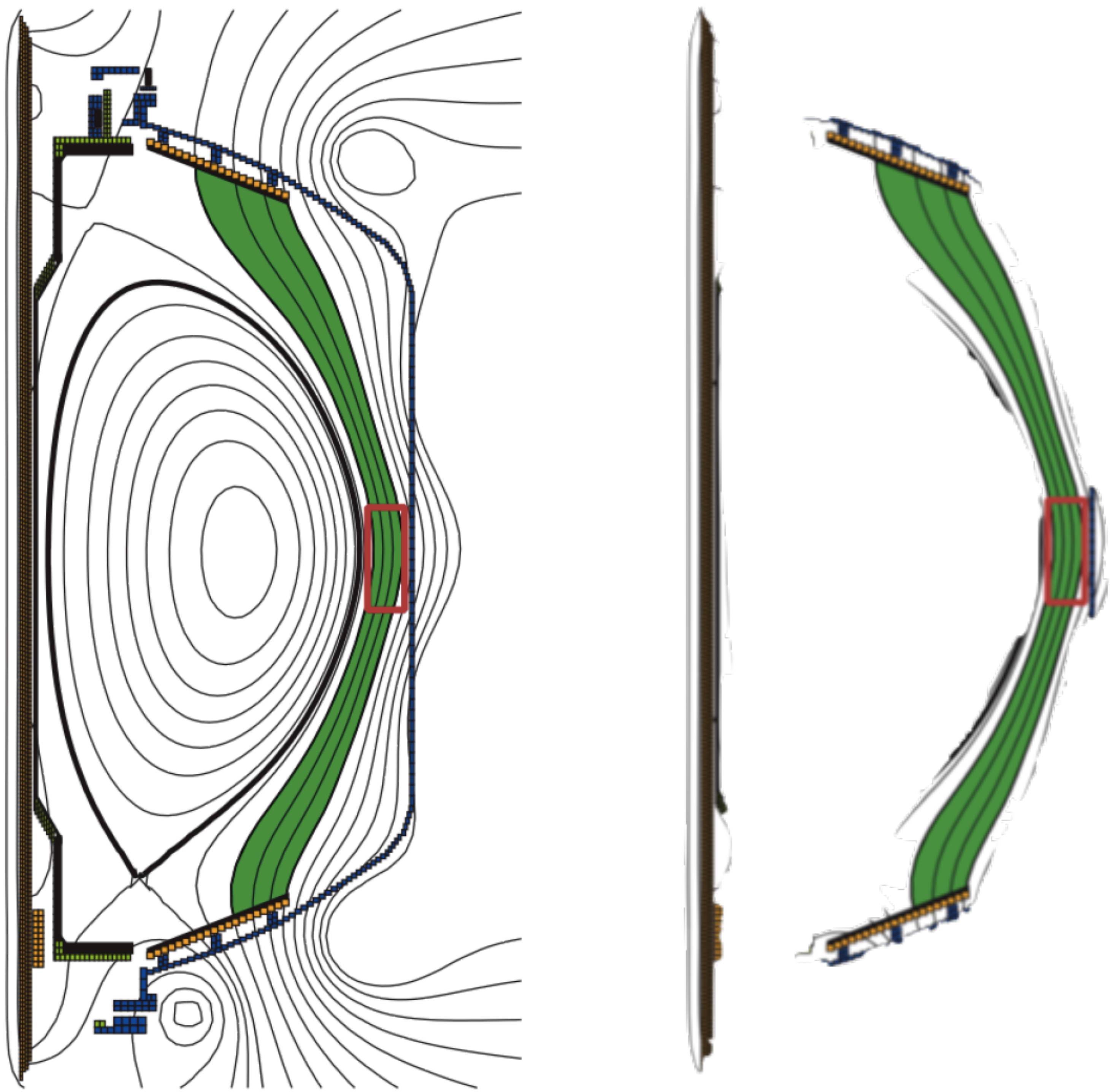
No cancellation problem!

Modeling the NSTX SOL with Gkeyll



Modeling the NSTX SOL with Gkeyll

- Open-field-line region only



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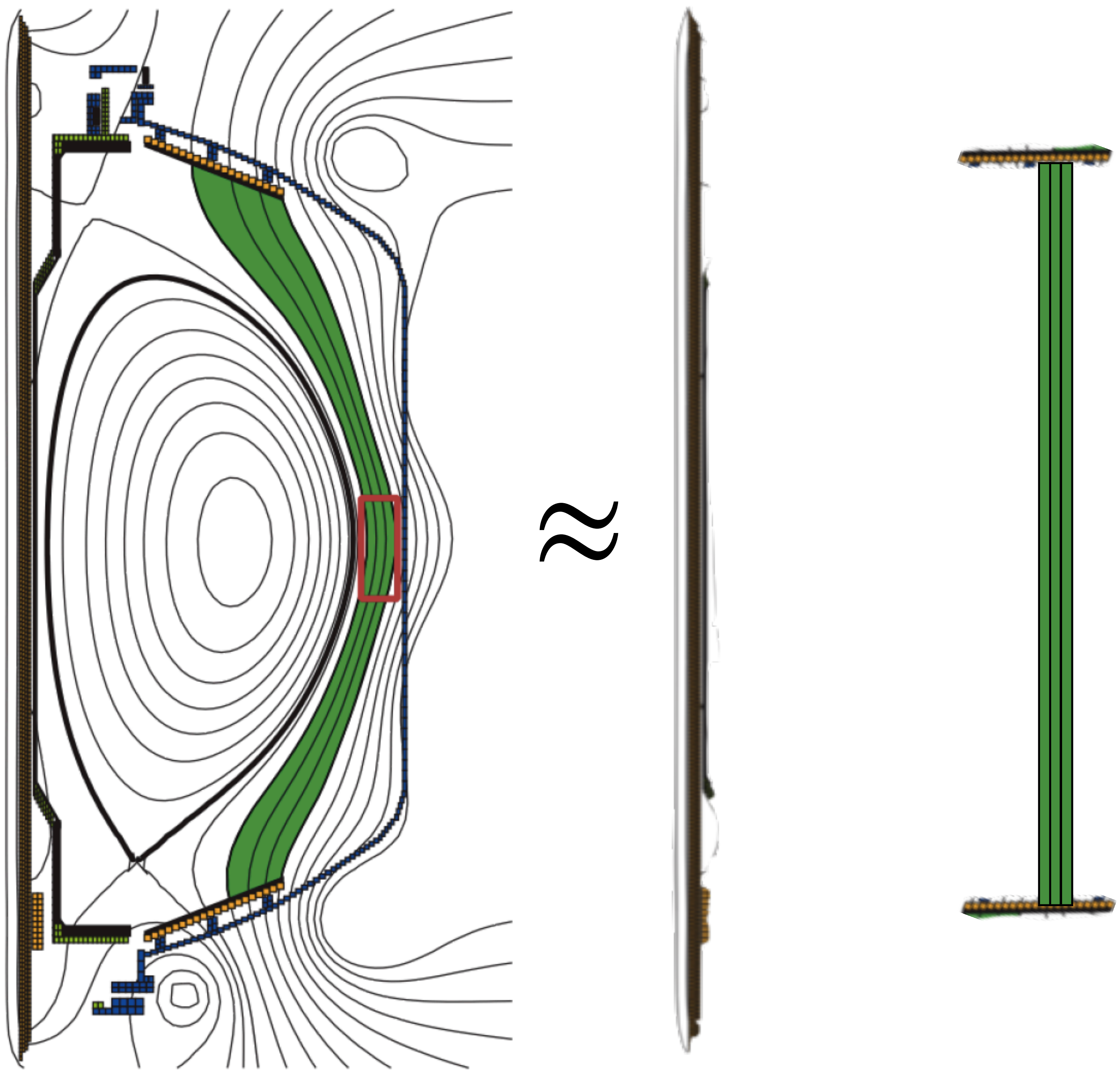

- Open-field-line region only
- Simplified helical geometry with vertical flux surfaces, const curvature and no shear (no X point)

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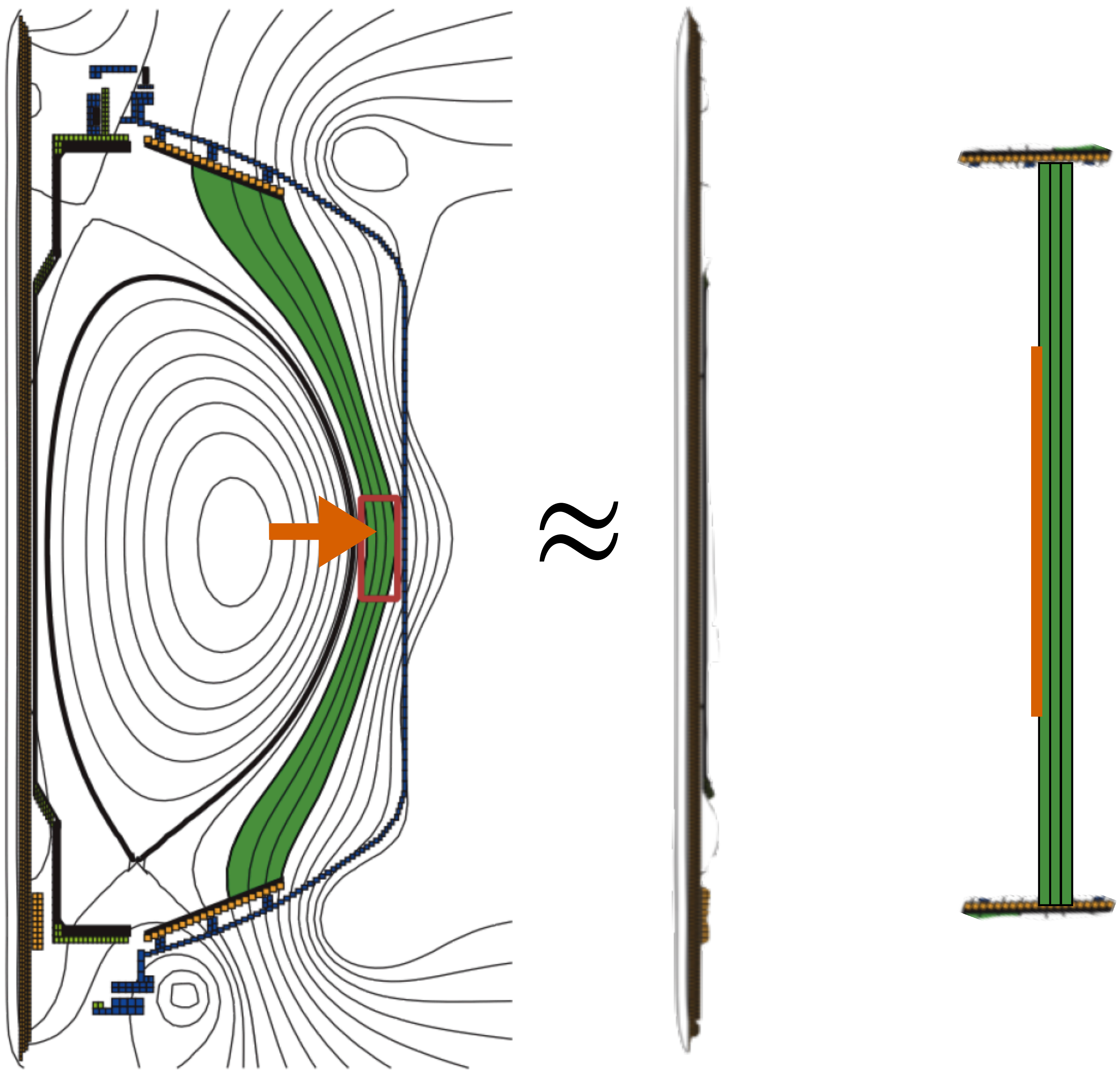

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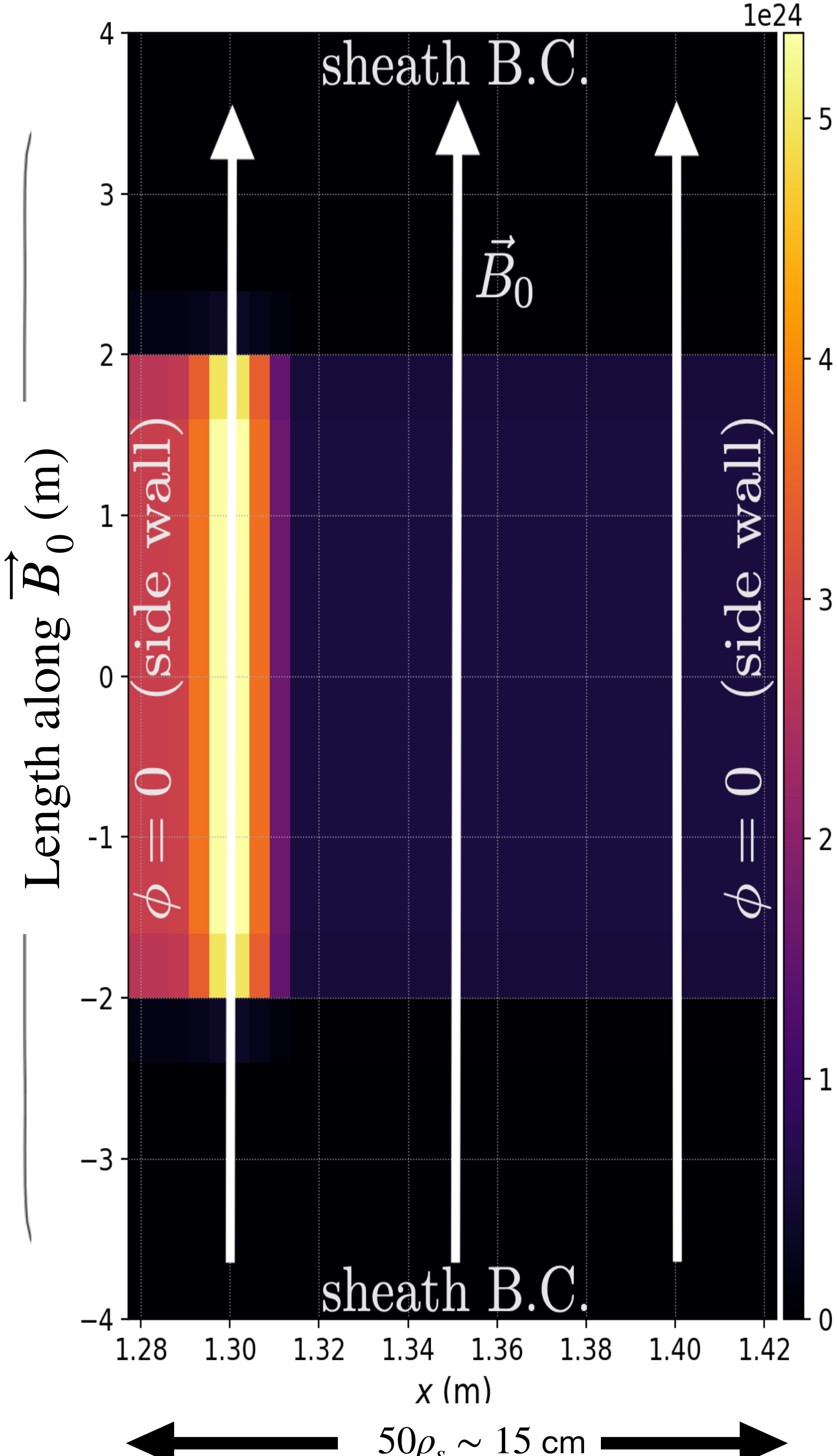

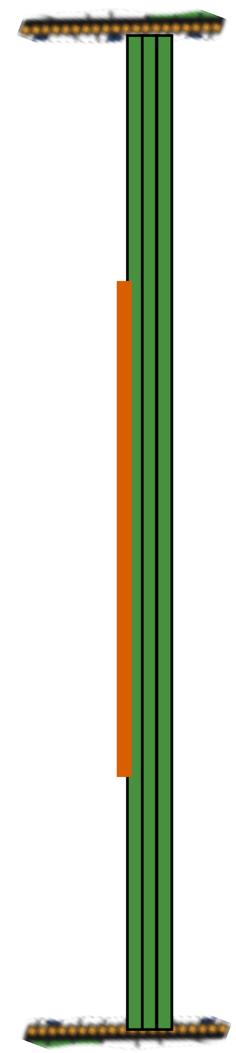

- Open-field-line region only
- Simplified helical geometry with vertical flux surfaces, const curvature and no shear (no X point)
- Model flux of heat and particles across separatrix with source
- Boundary conditions:
  - perfectly conducting walls ($\phi = A_{||} = 0$) in radial direction, *x*
  - periodic in binormal direction, *y*
  - conducting sheath model BC along field line, *z*

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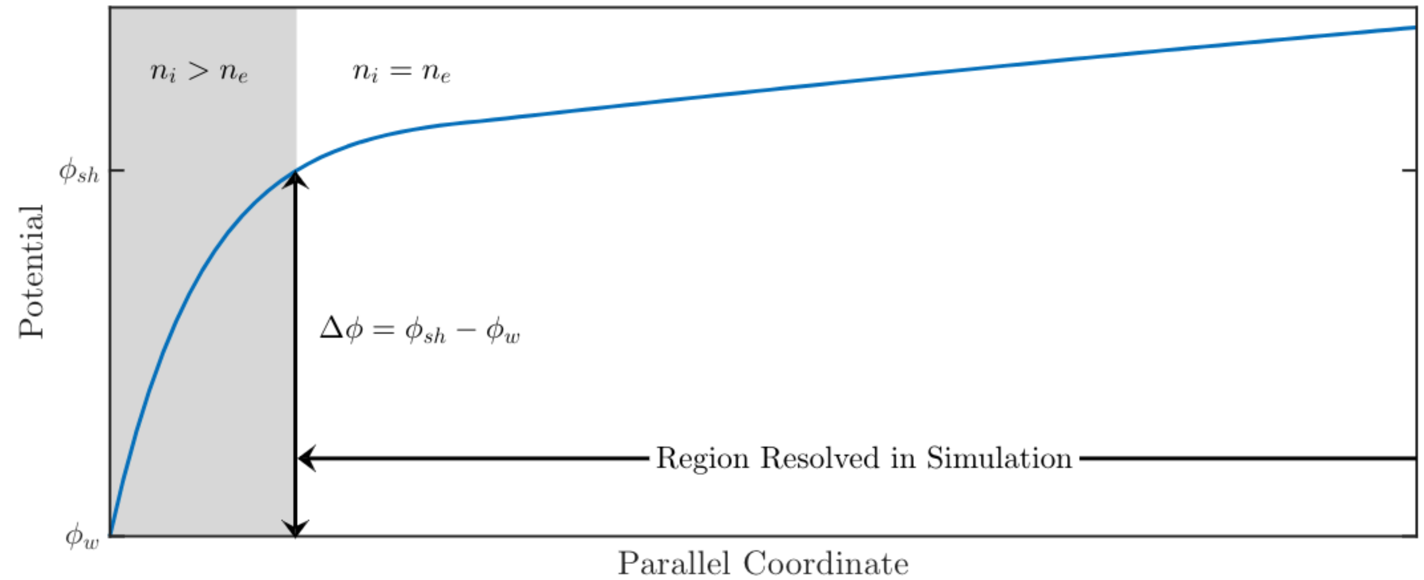
Conducting-sheath boundary condition



E. Shi

- Need to model non-neutral sheath using BCs (GK assumes quasi-neutrality, cannot resolve sheath)

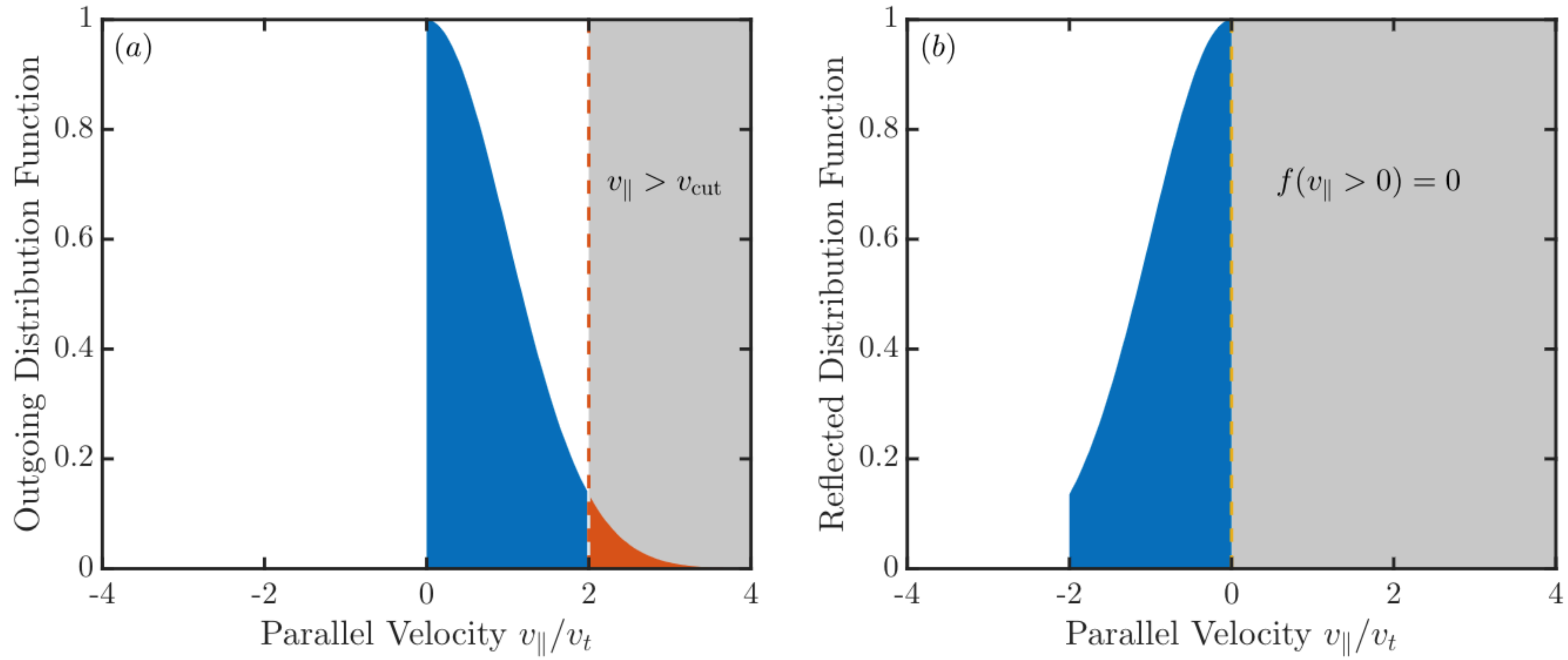
- Sheath potential should reflect low energy electrons

- Solve Poisson equation on z boundary to get $\phi_{sh}(x, y) \doteq \phi(z = z_{sh})$, then use $\Delta\phi = \phi_{sh} - \phi_w$ to reflect electrons with $mv_{\|}^2/2 < |e|\Delta\phi$

$$-\nabla_\perp \cdot \sum_s \frac{m_s n_{0s}}{B^2} \nabla_\perp \phi(z = z_{sh}) = \sum_s q_s \int d^3v \; f_s(z = z_{sh})$$

- Potential self-consistently relaxes to ambipolar-parallel-outflow state, and allows local currents in and out of wall (unlike “logical” sheath model)

Sheath boundary condition for electrons



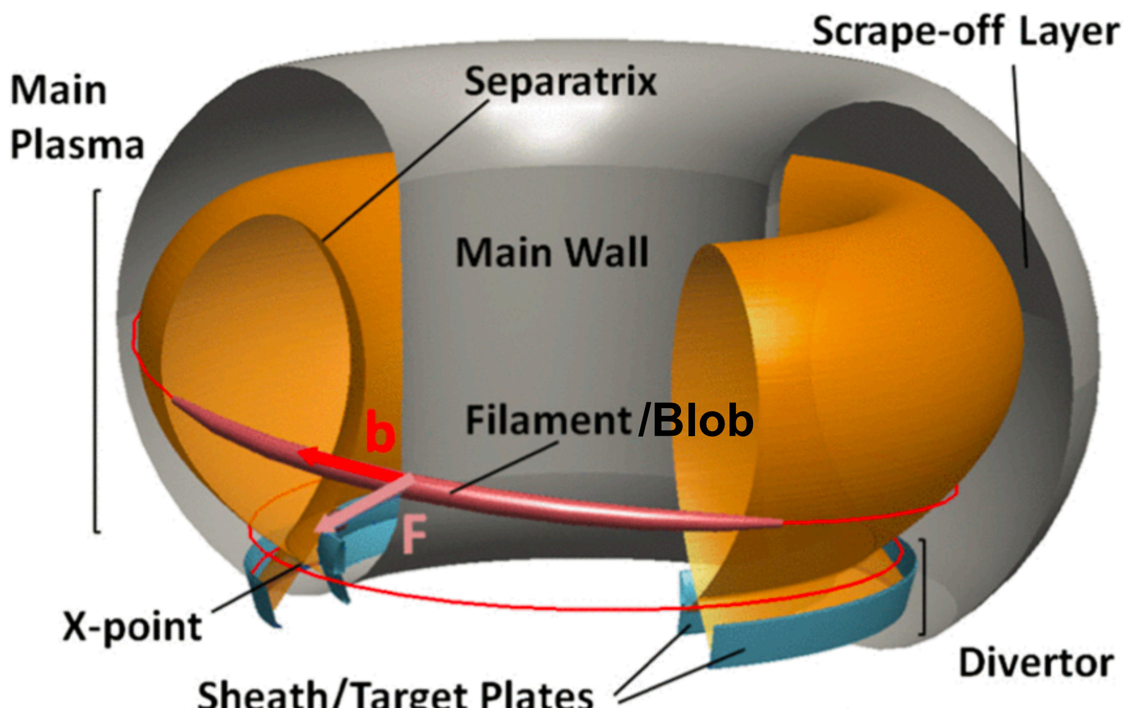
E. Shi

(a) Outgoing electrons with $v_{||} > v_{cut} = \sqrt{2e\Delta\phi/m}$ are lost into the wall

(b) Rest of outgoing electrons $0 < v_{||} < v_{cut}$ are reflected back into plasma

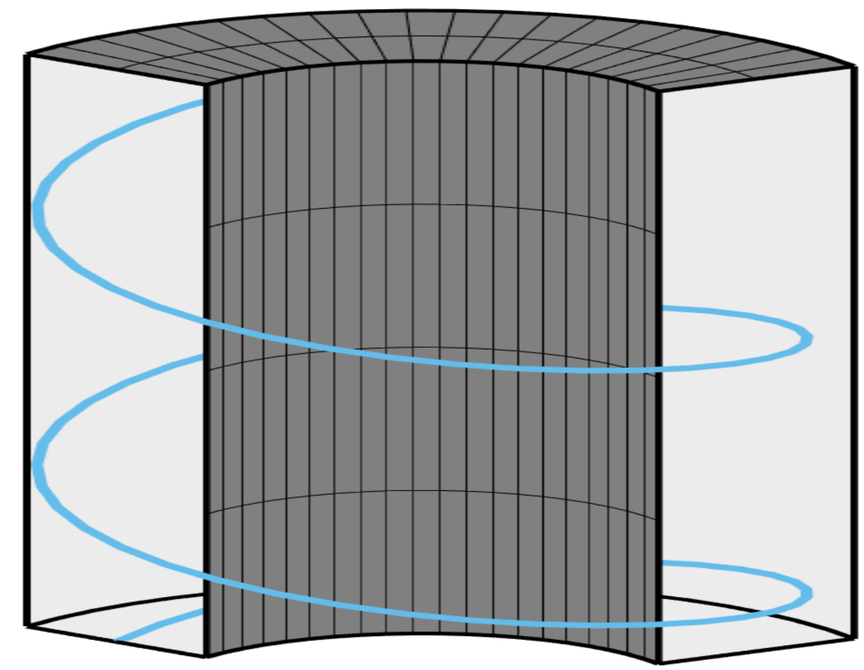
Ions: Assuming positive sheath potential (relative to wall), all ions are lost

Modeling the NSTX SOL with Gkeyll



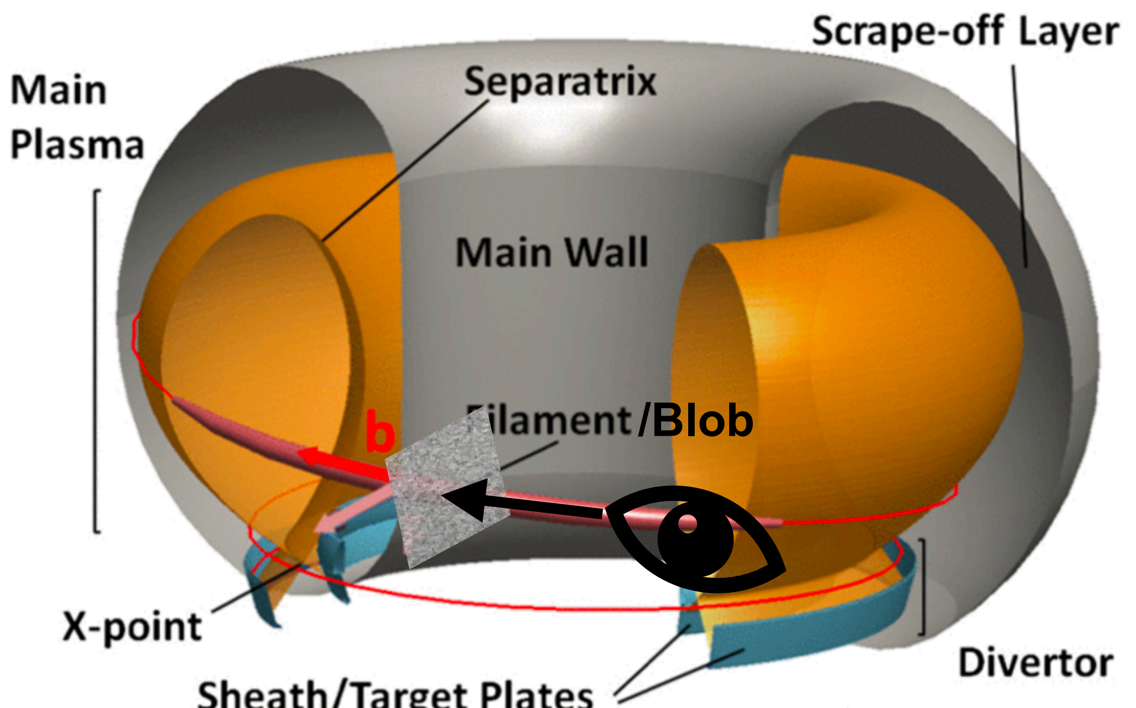
Carralero et al, 2015

$\approx$



- Simple helical model of NSTX SOL
    - Field-aligned simulation domain that follows field lines from bottom divertor plate, around the torus, to the top divertor plate
    - Length along field line ~ connection length $L_{||} = 8$ m (constant, no shear for now)
    - All bad curvature → interchange instability, blob dynamics
    - Real deuterium mass ratio, Lenard-Bernstein collisions

Modeling the NSTX SOL with Gkeyll



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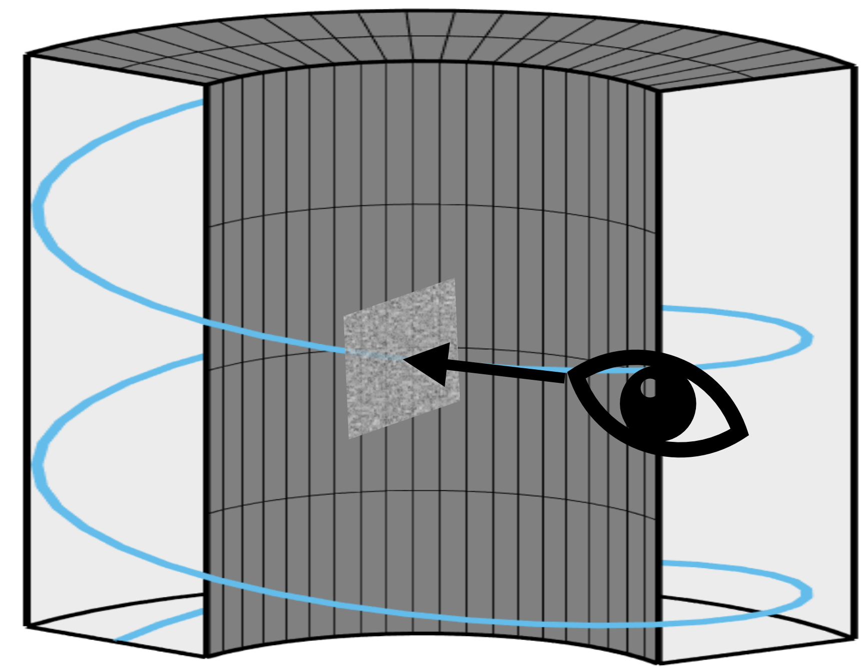

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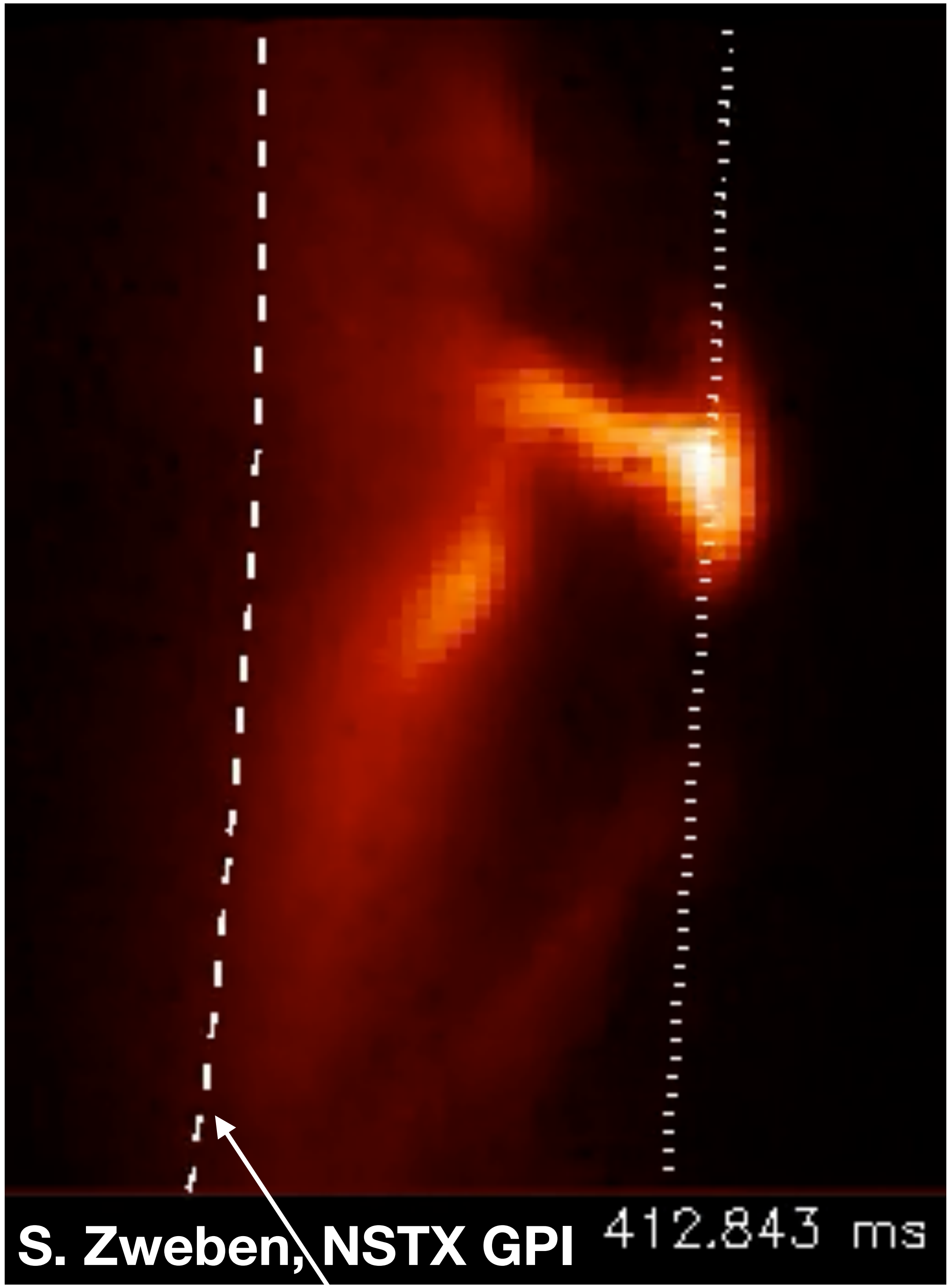
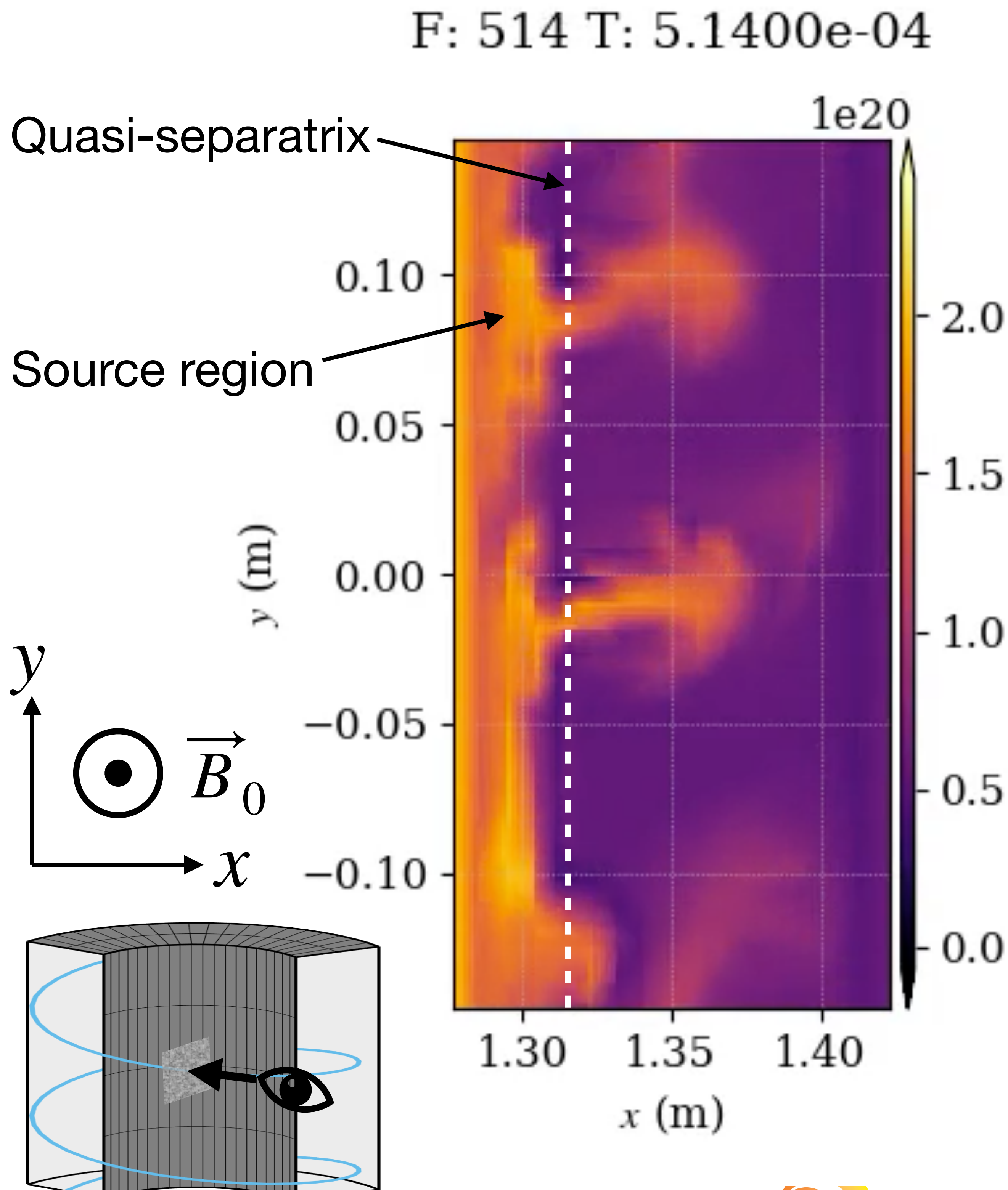
NSTX GPI vs Gkeyll

Dα signal ~ density at midplane



Ion density at midplane



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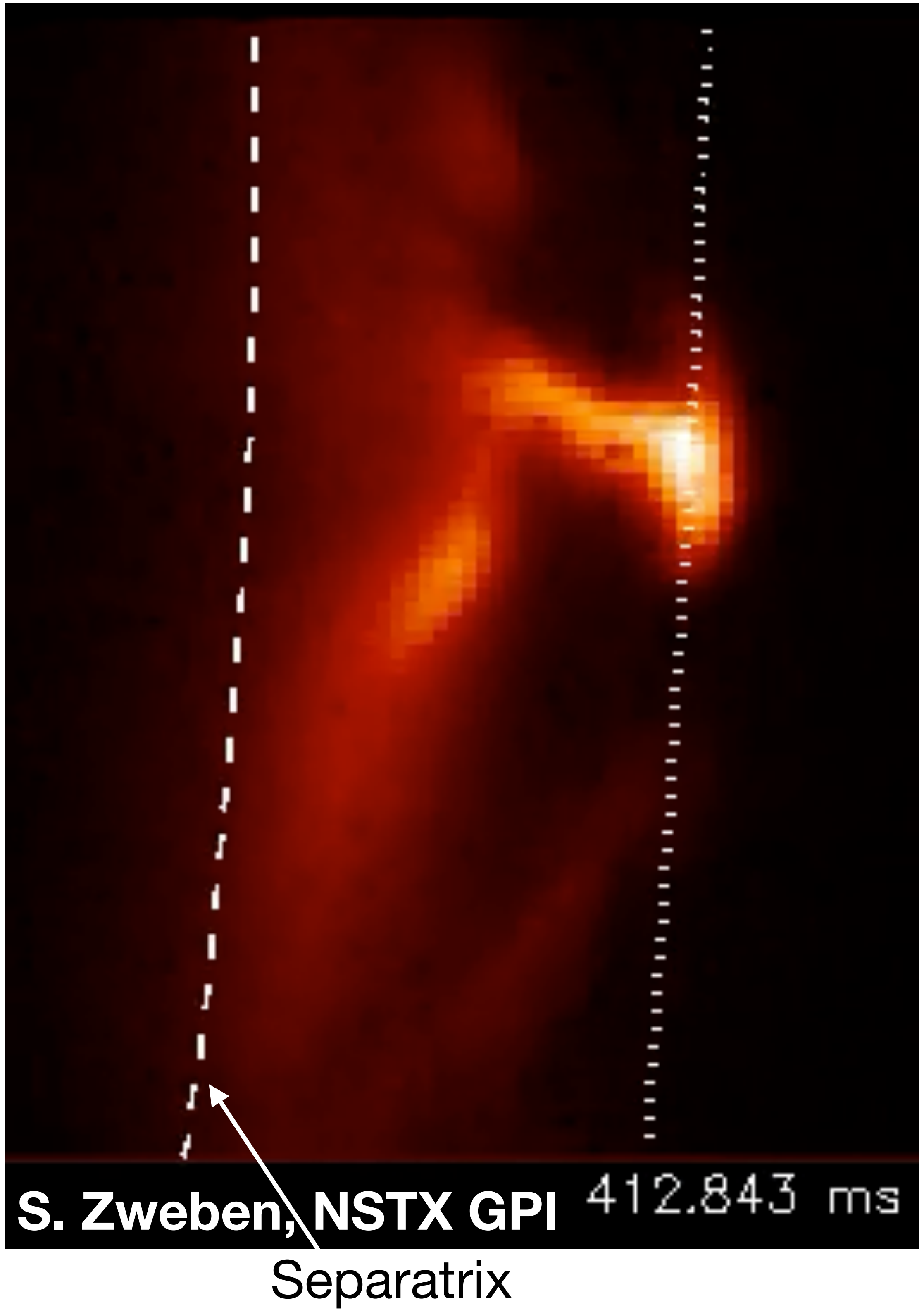

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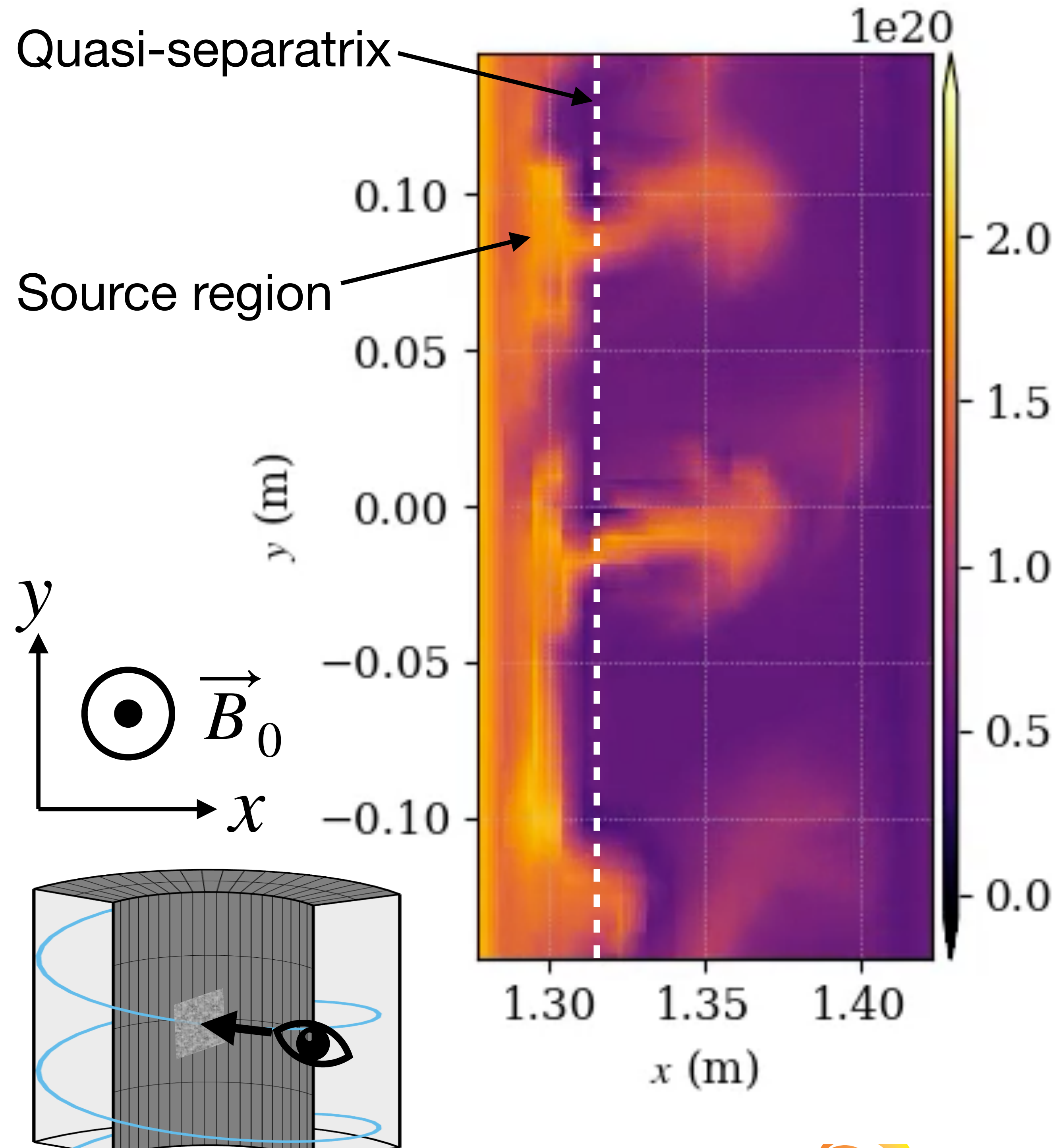
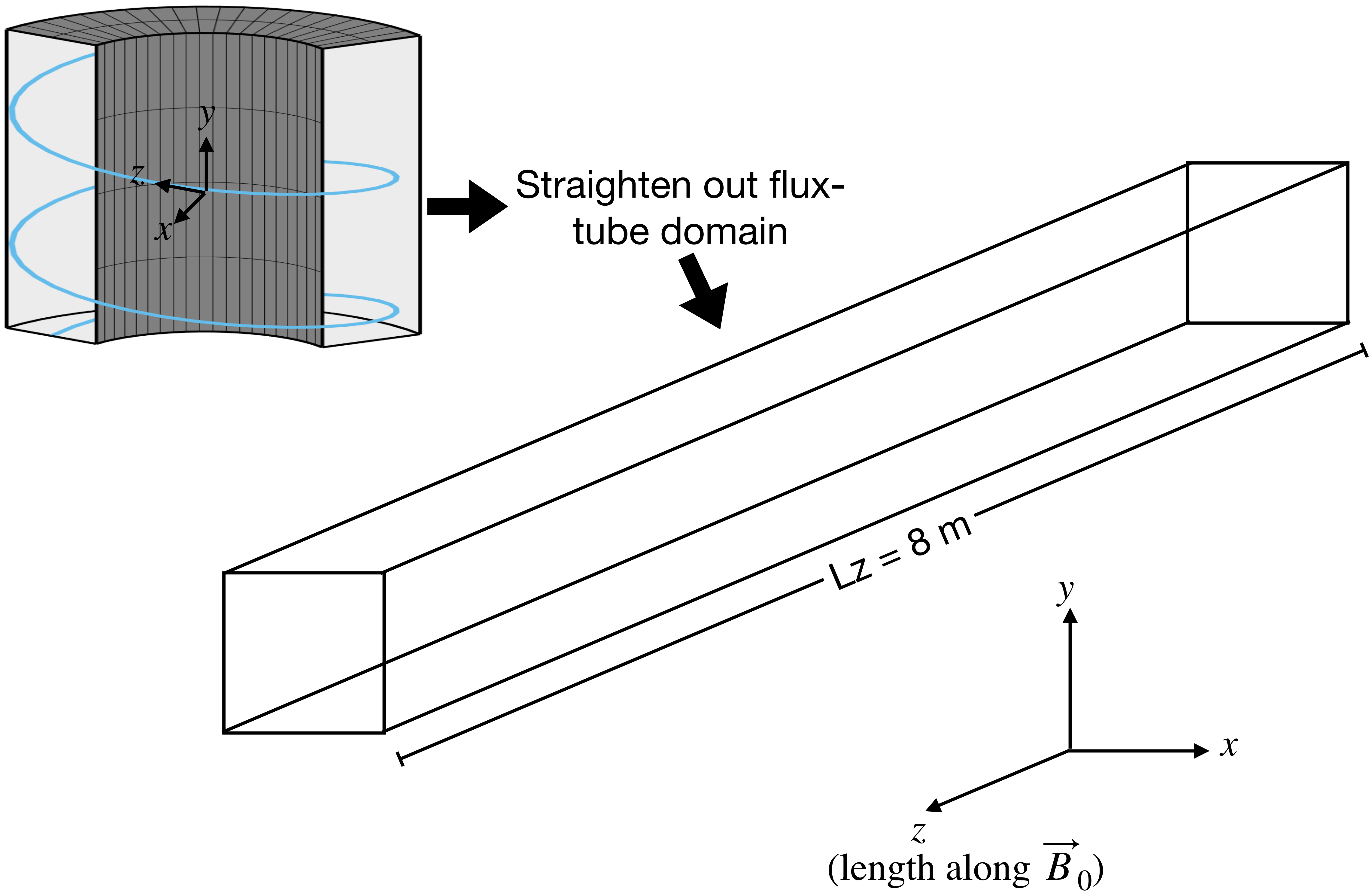


Demonstrating Gkeyll's EMGK capabilities: tracing magnetic field lines



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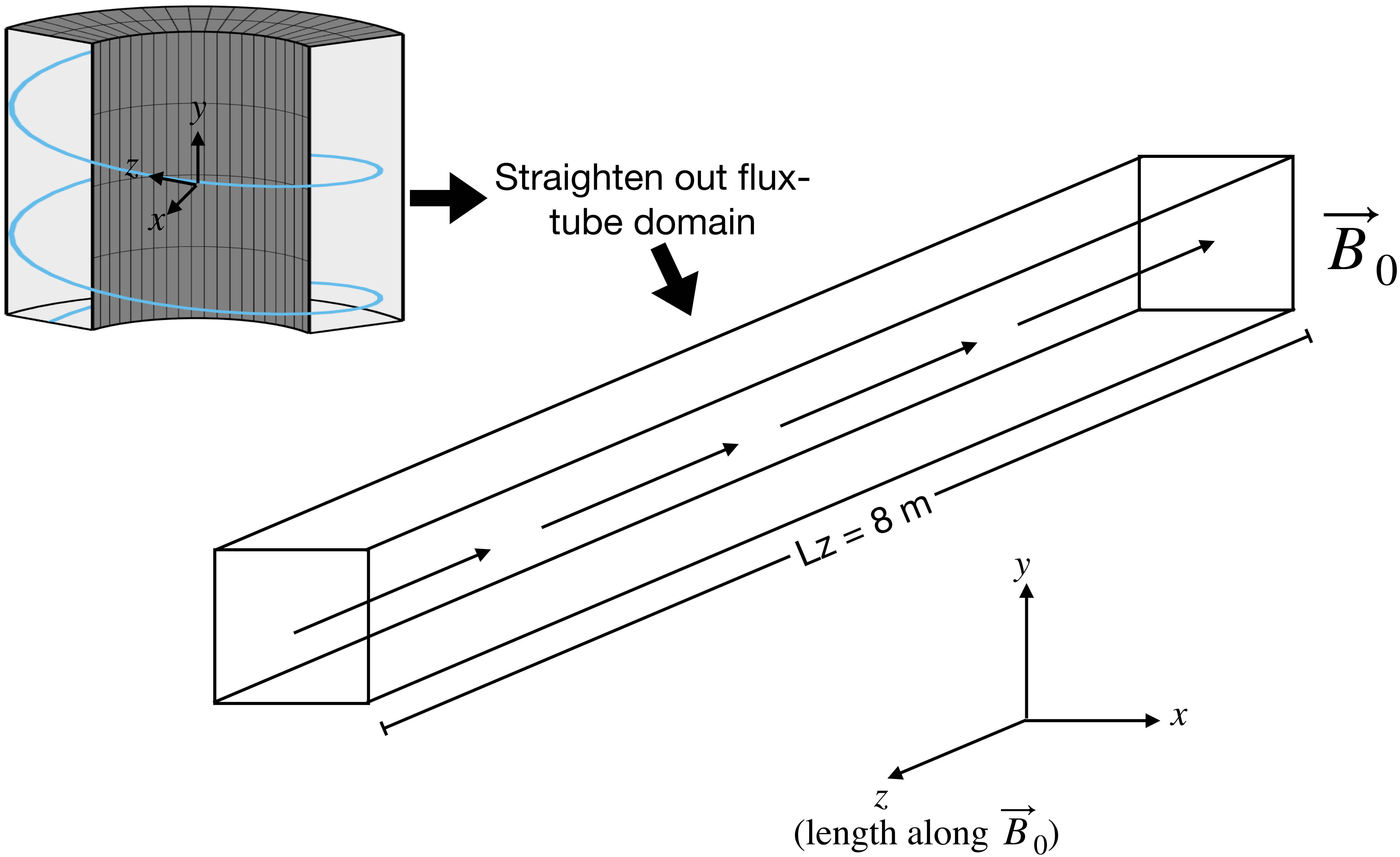

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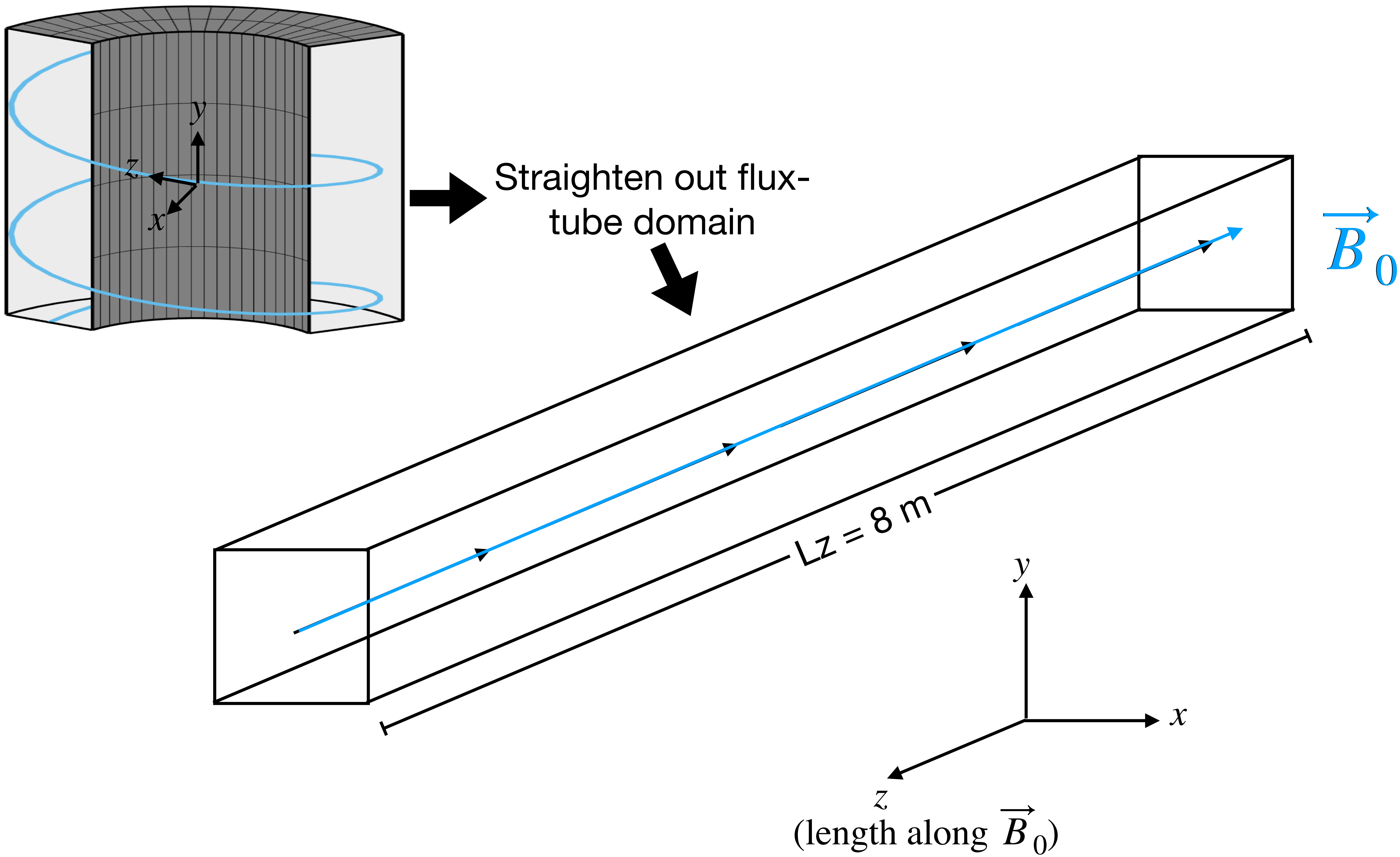

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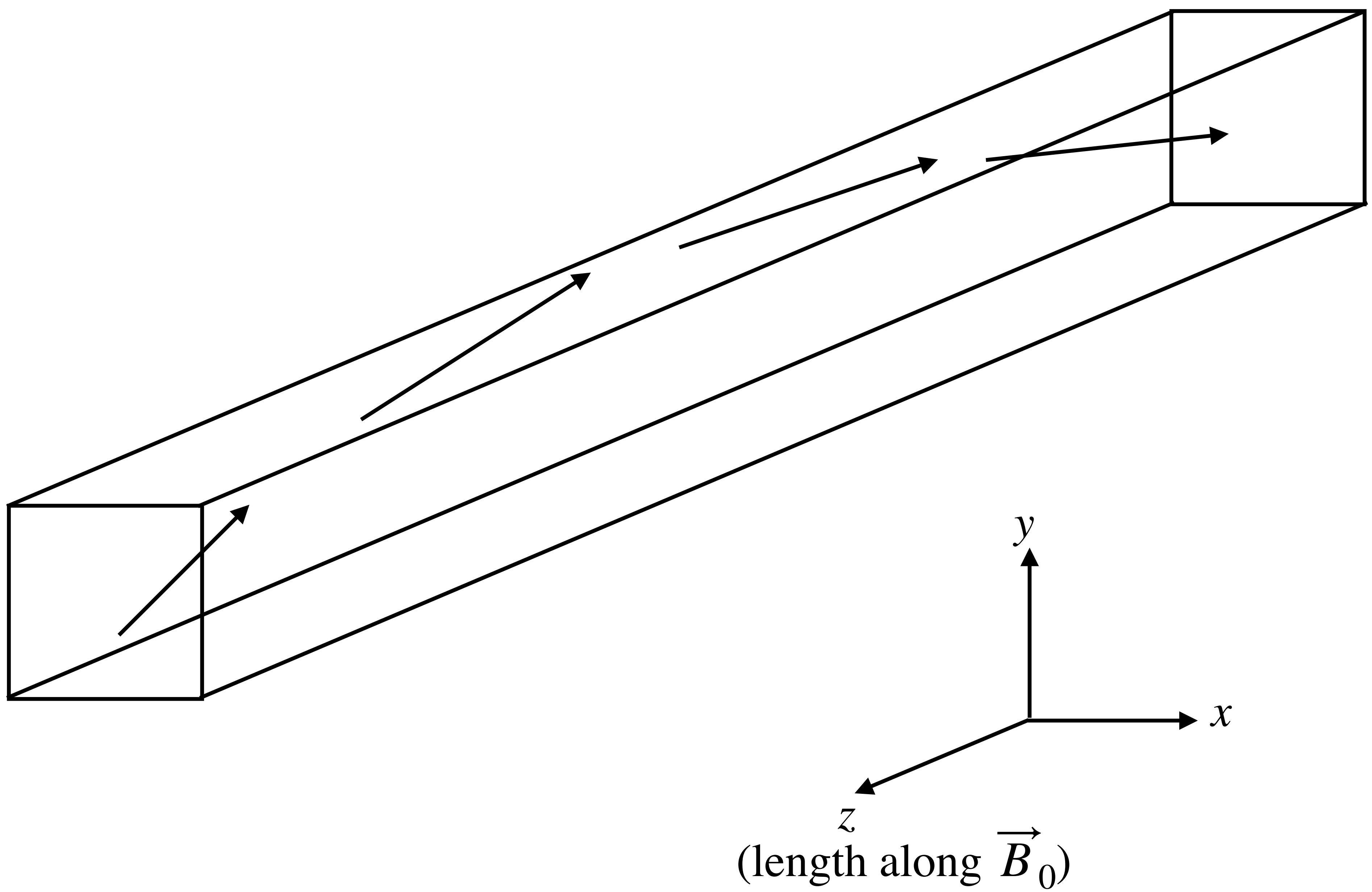

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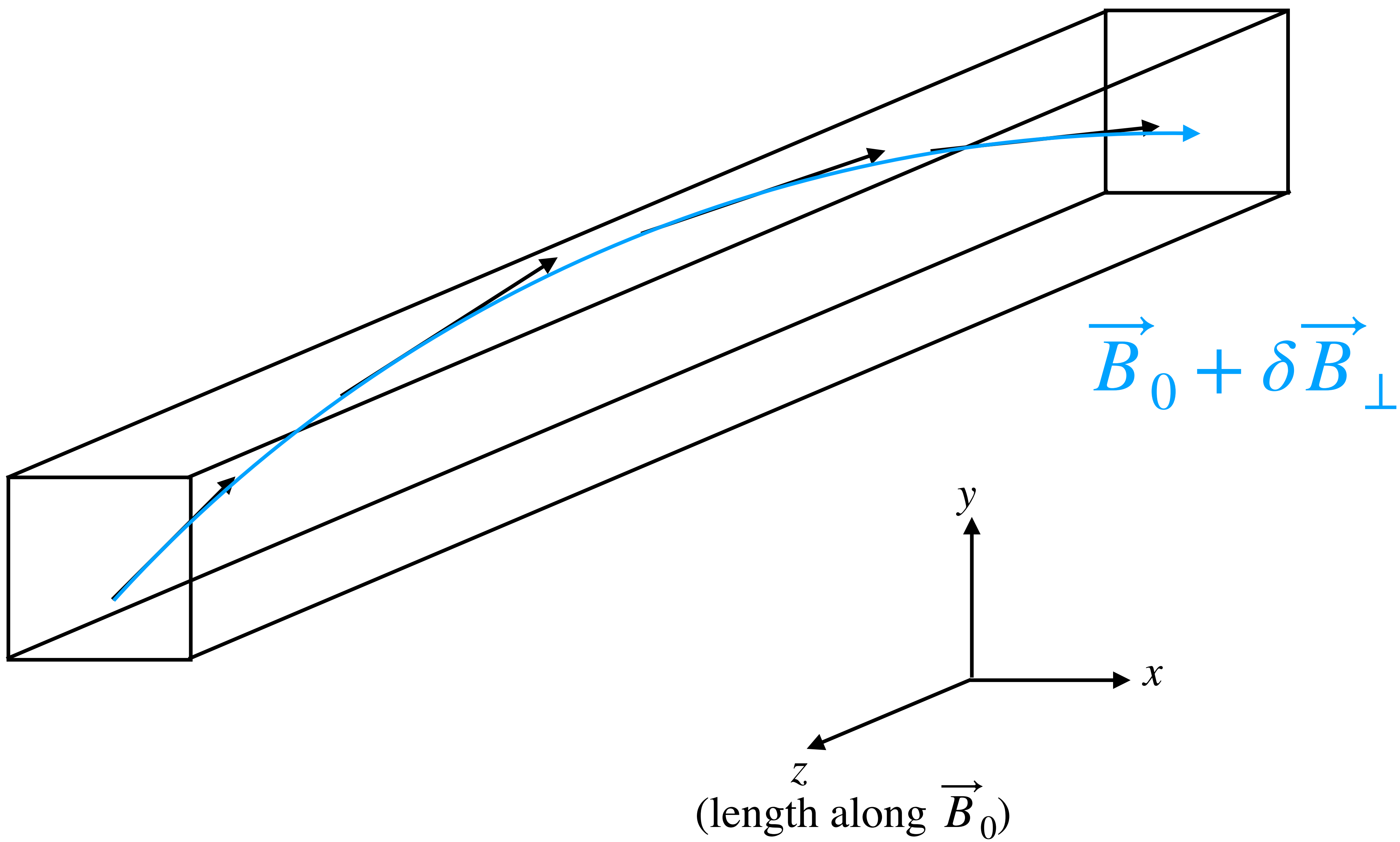

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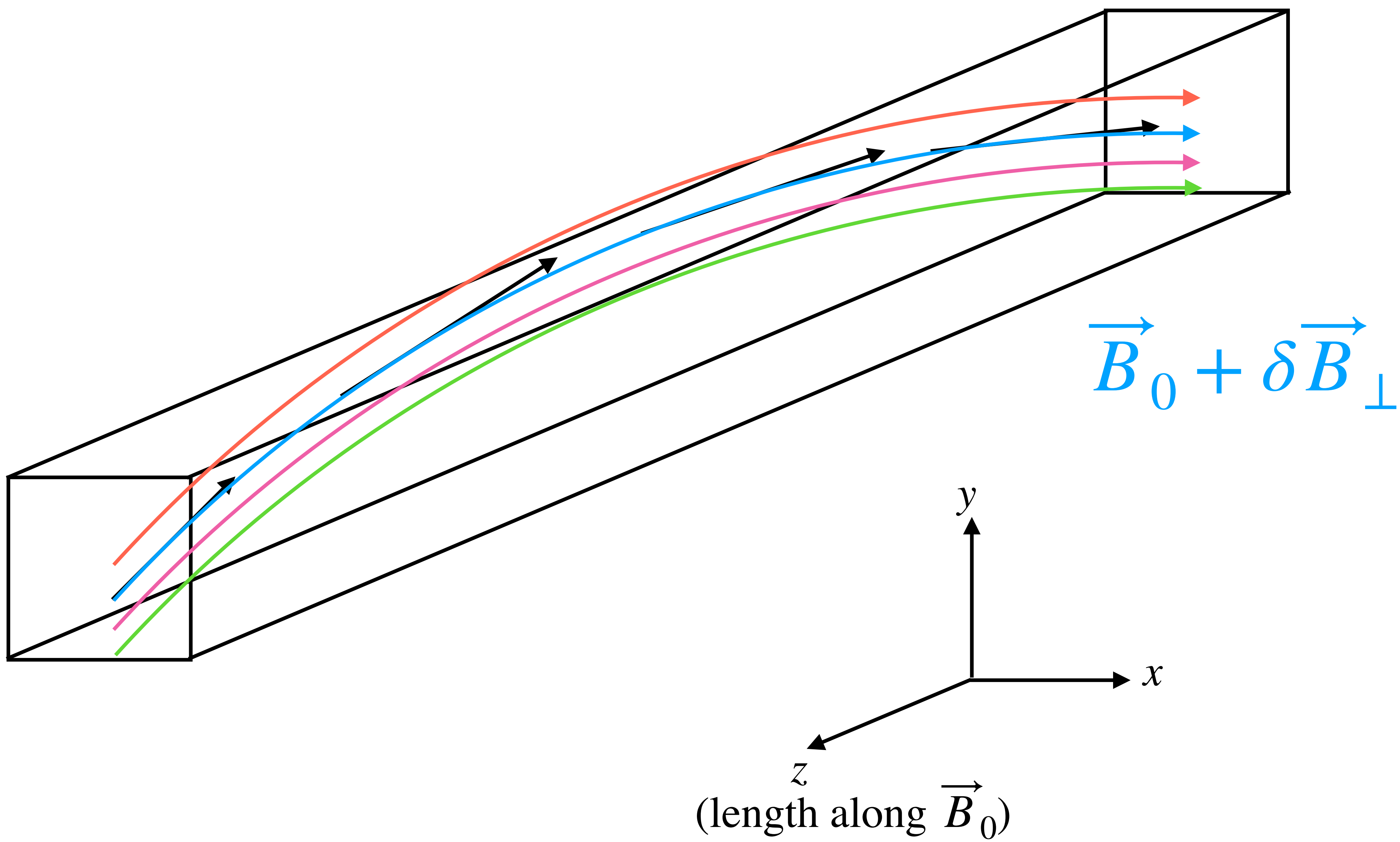

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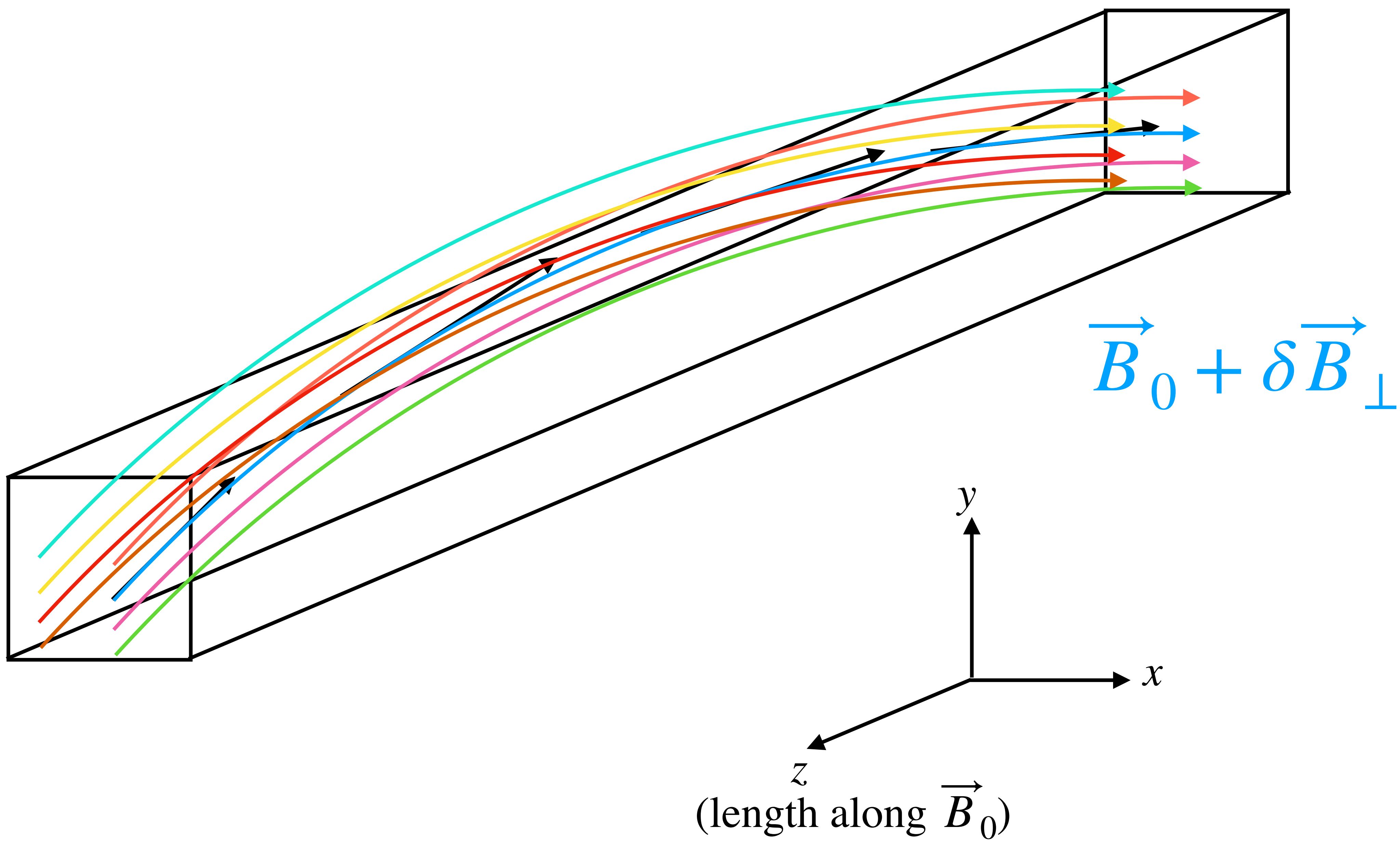

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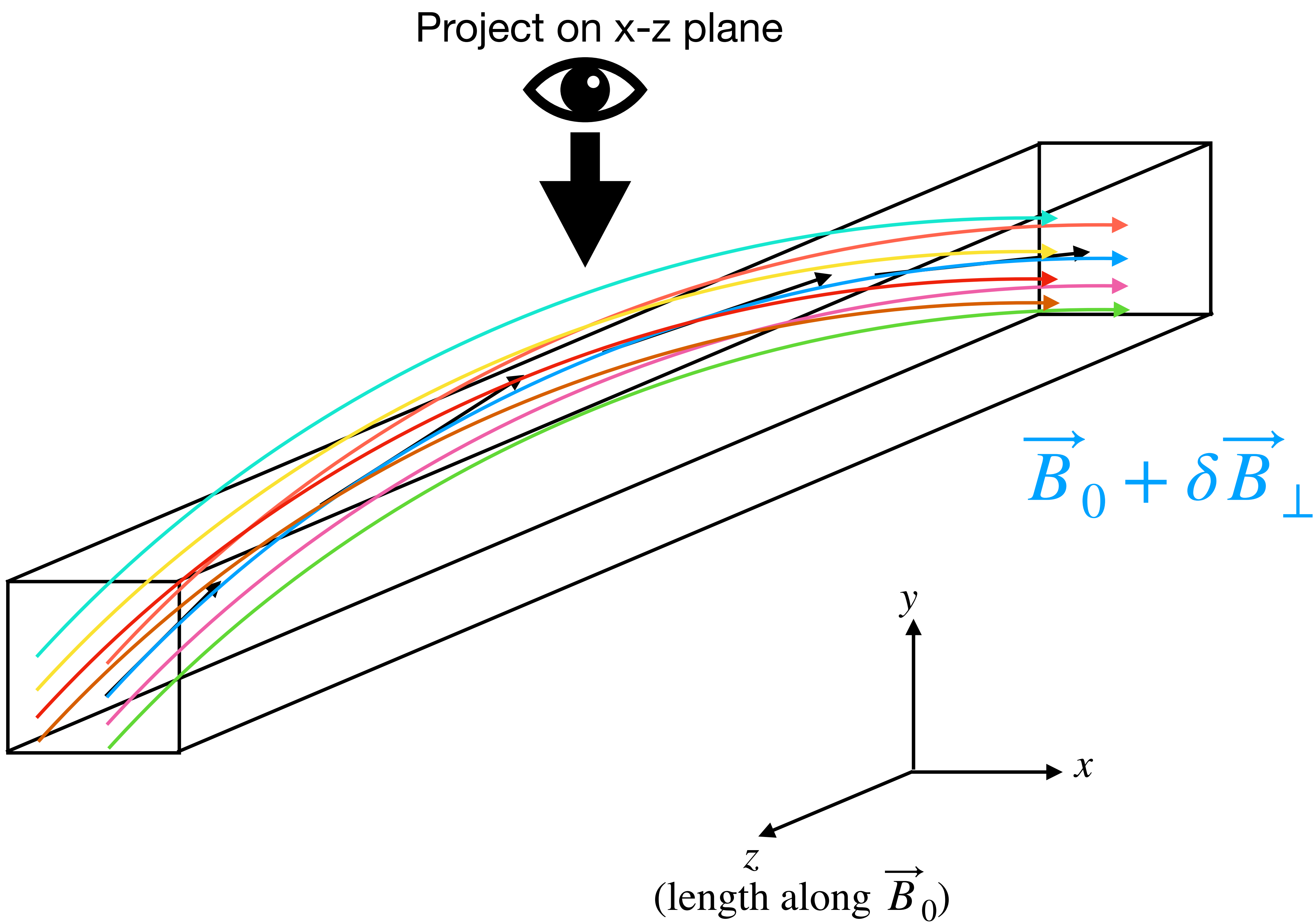

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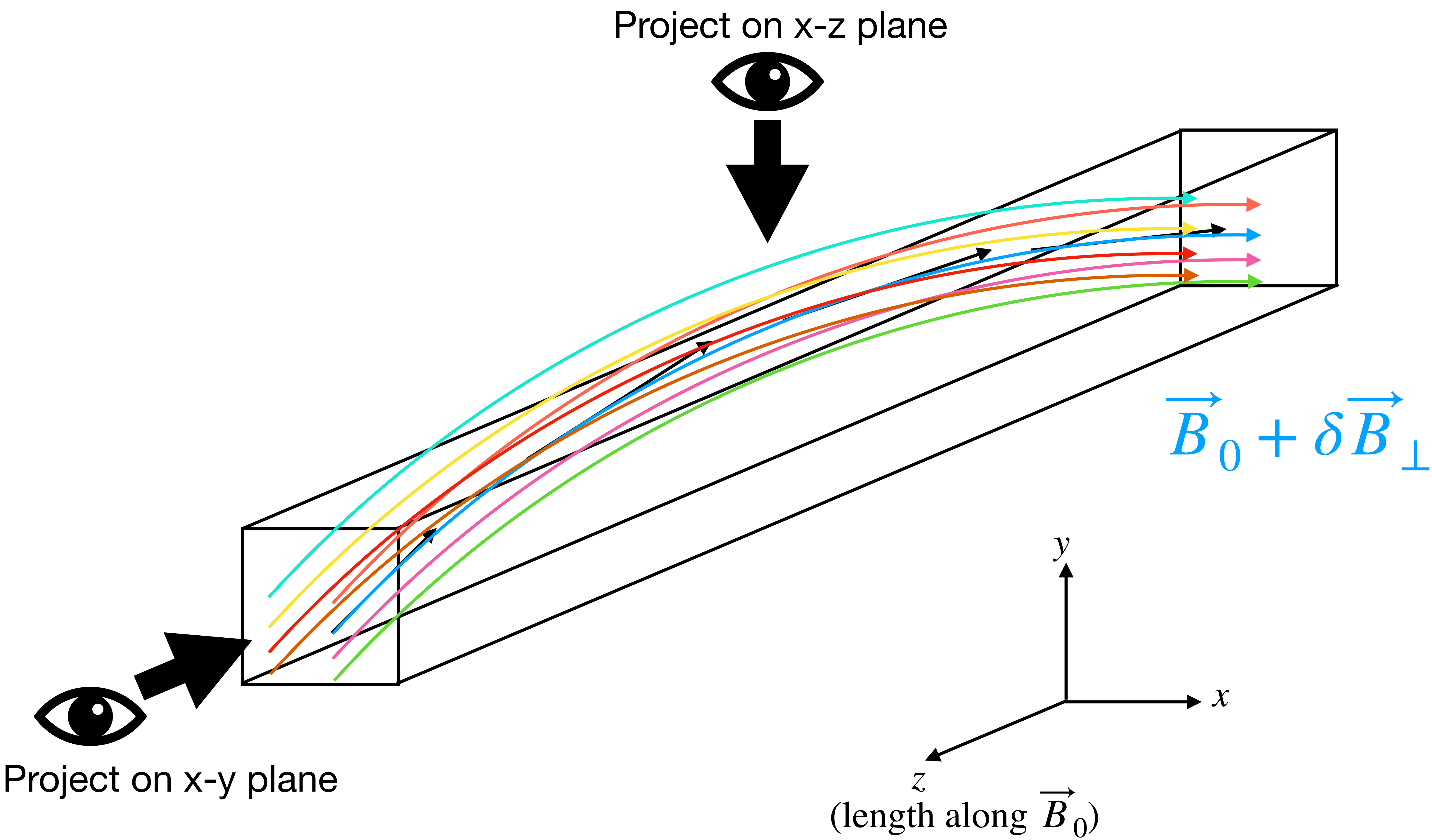
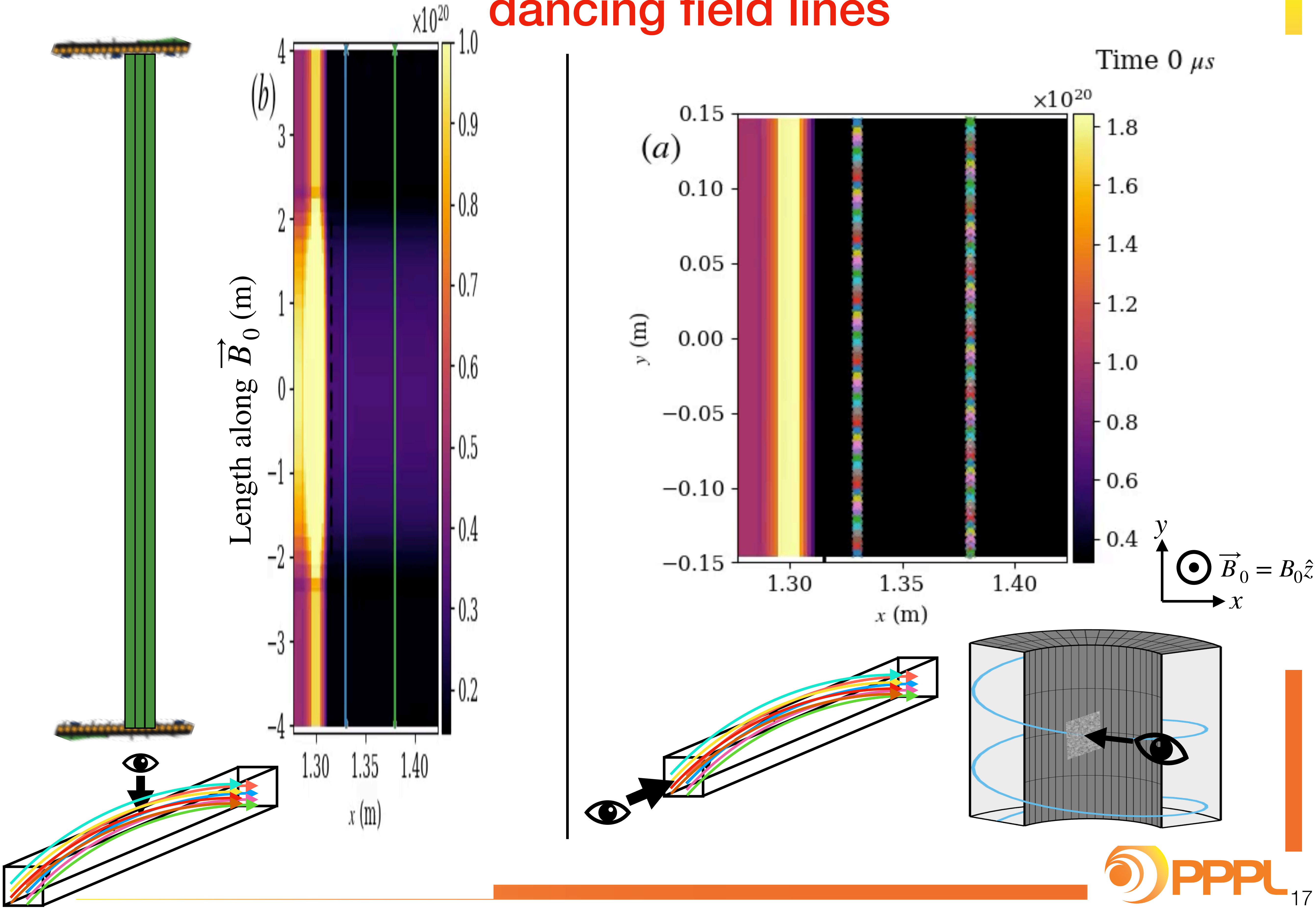


Demonstrating Gkeyll's EMGK capabilities: dancing field lines



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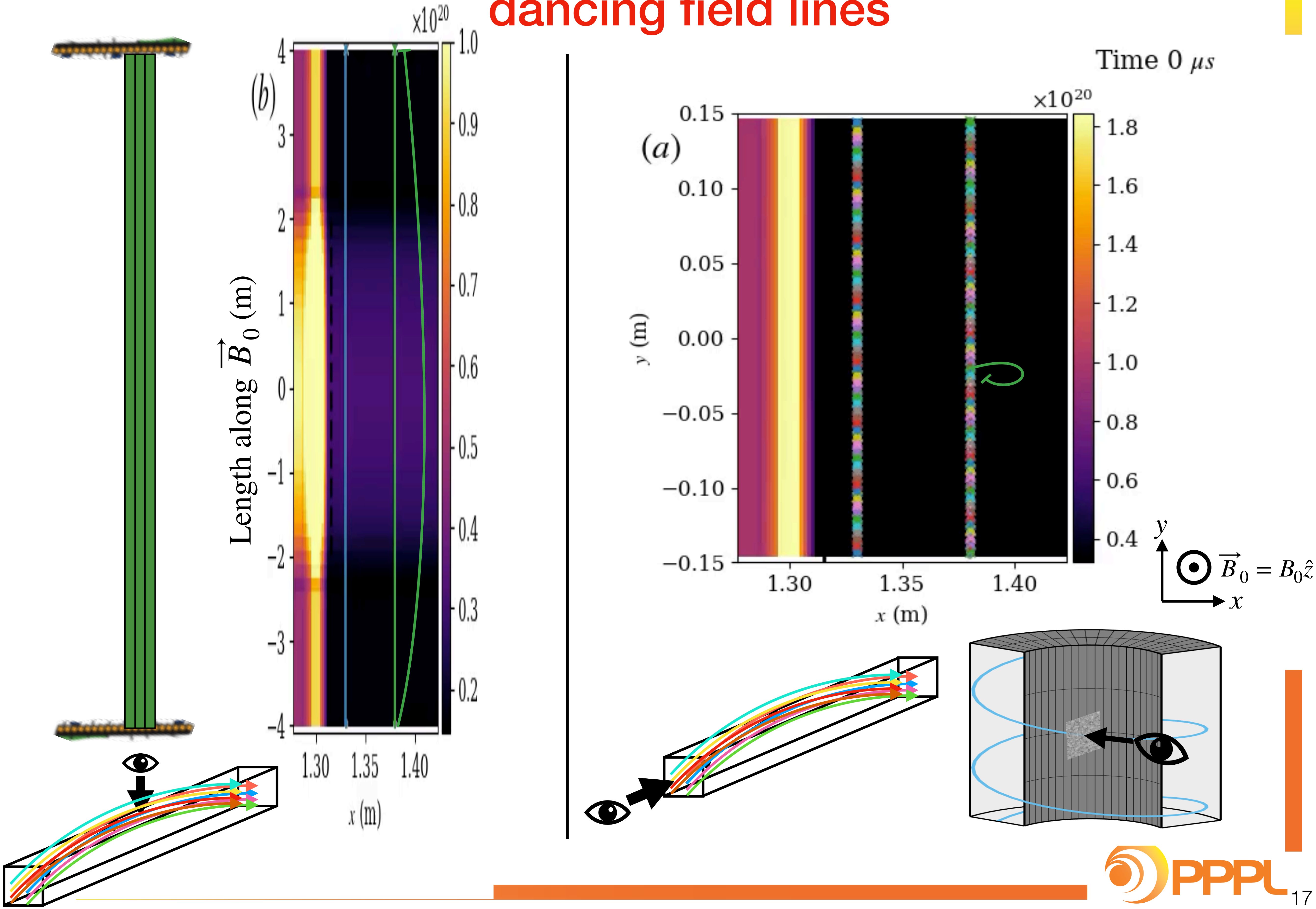

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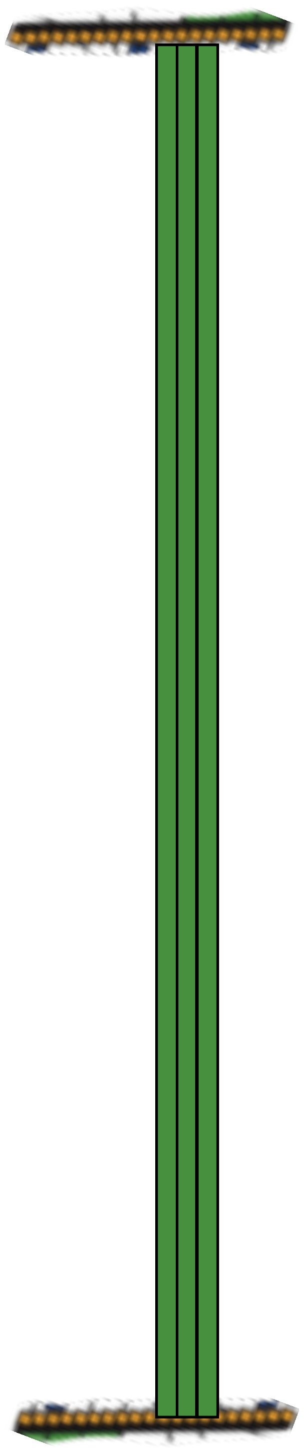

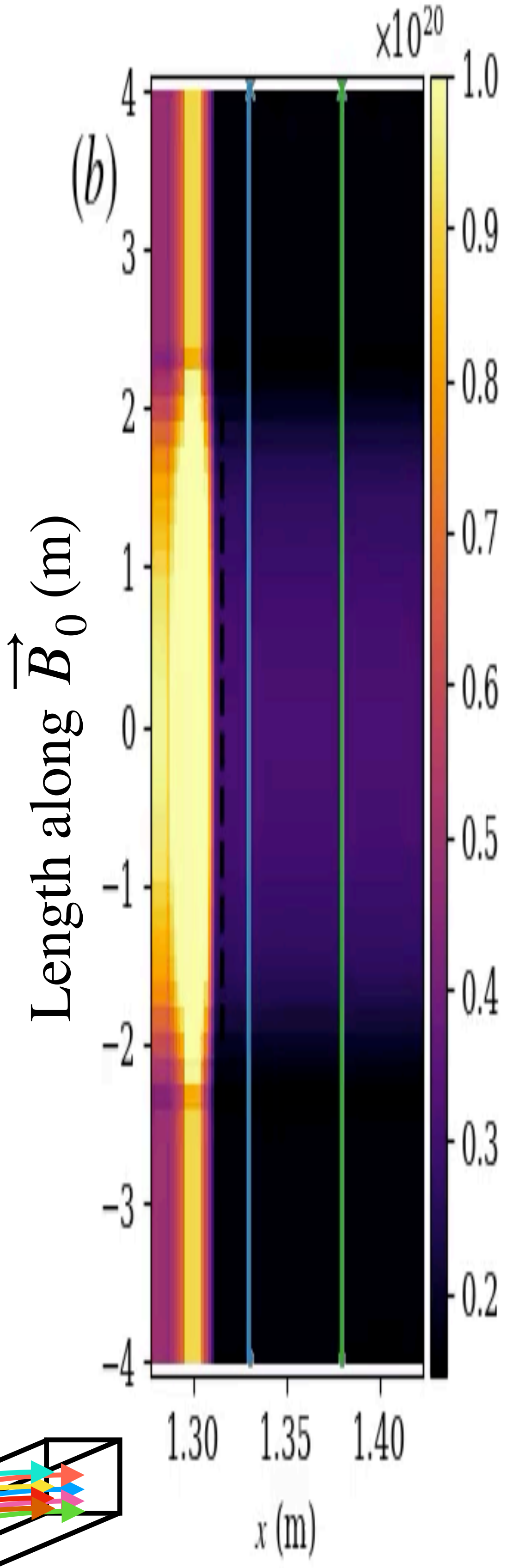

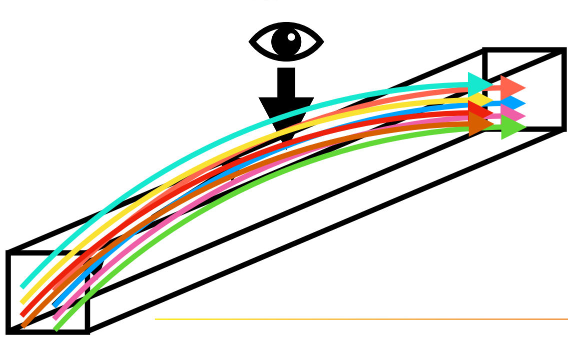

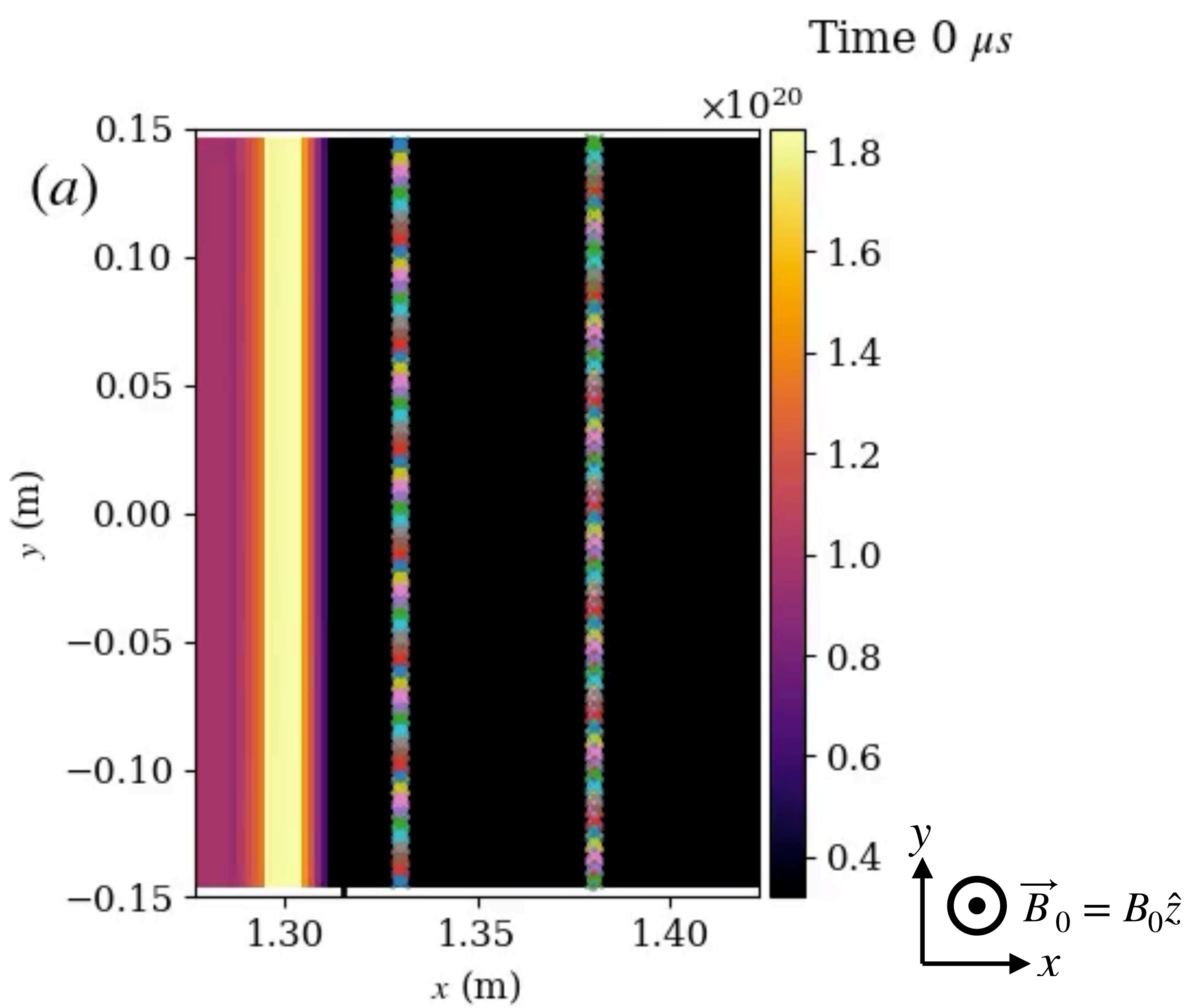

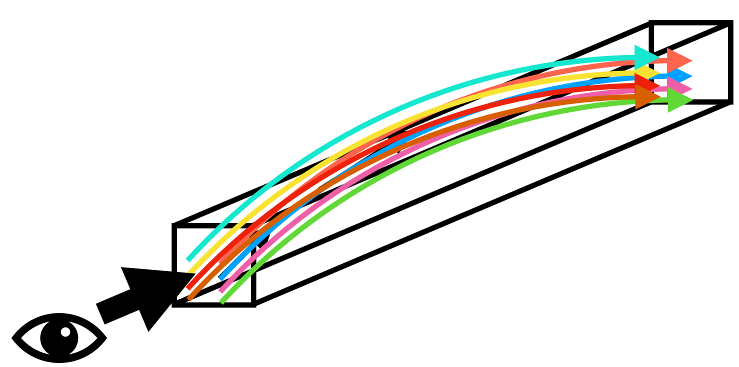

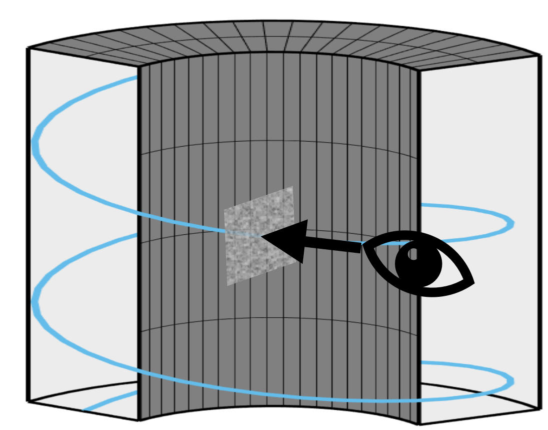

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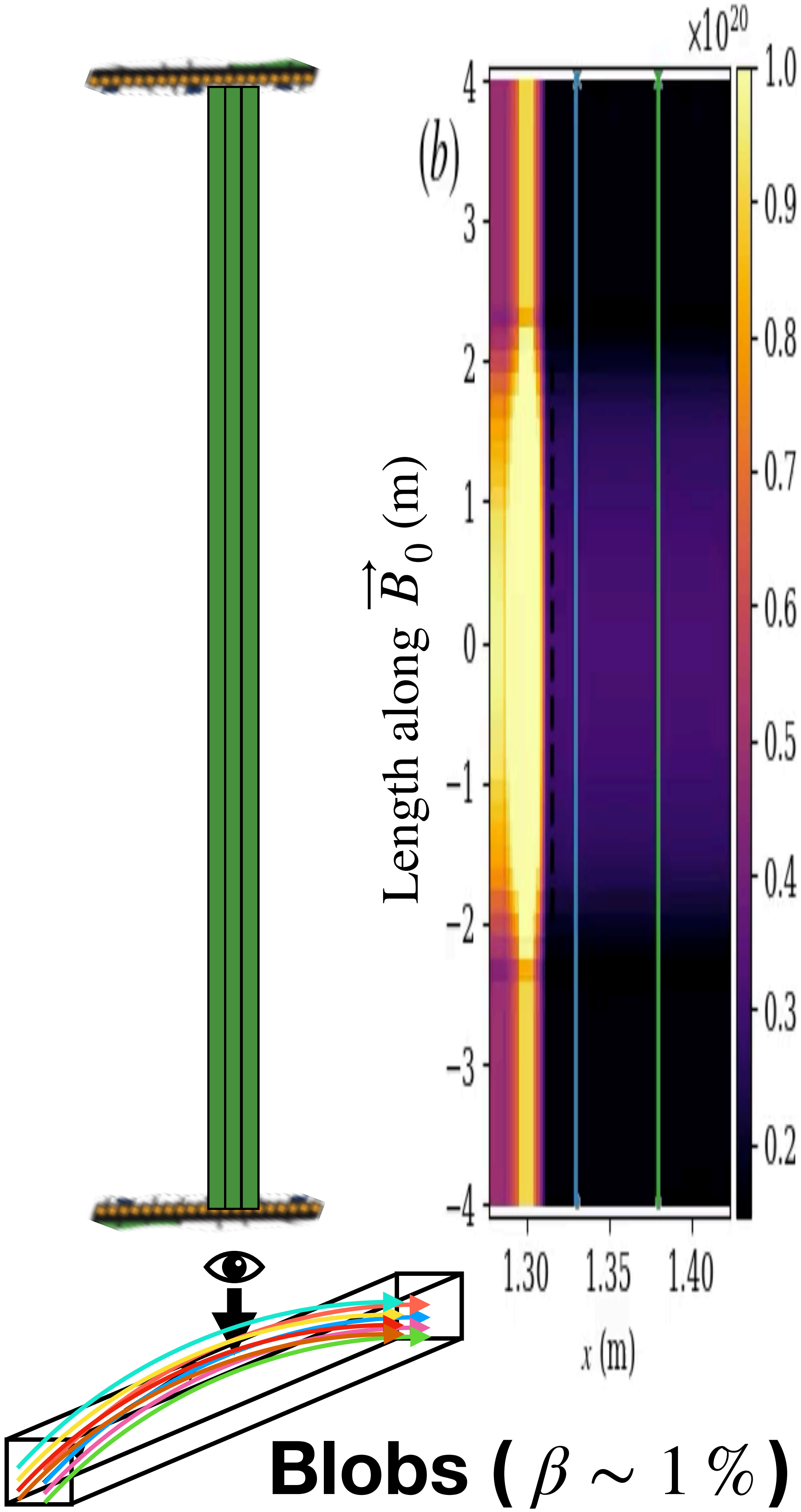

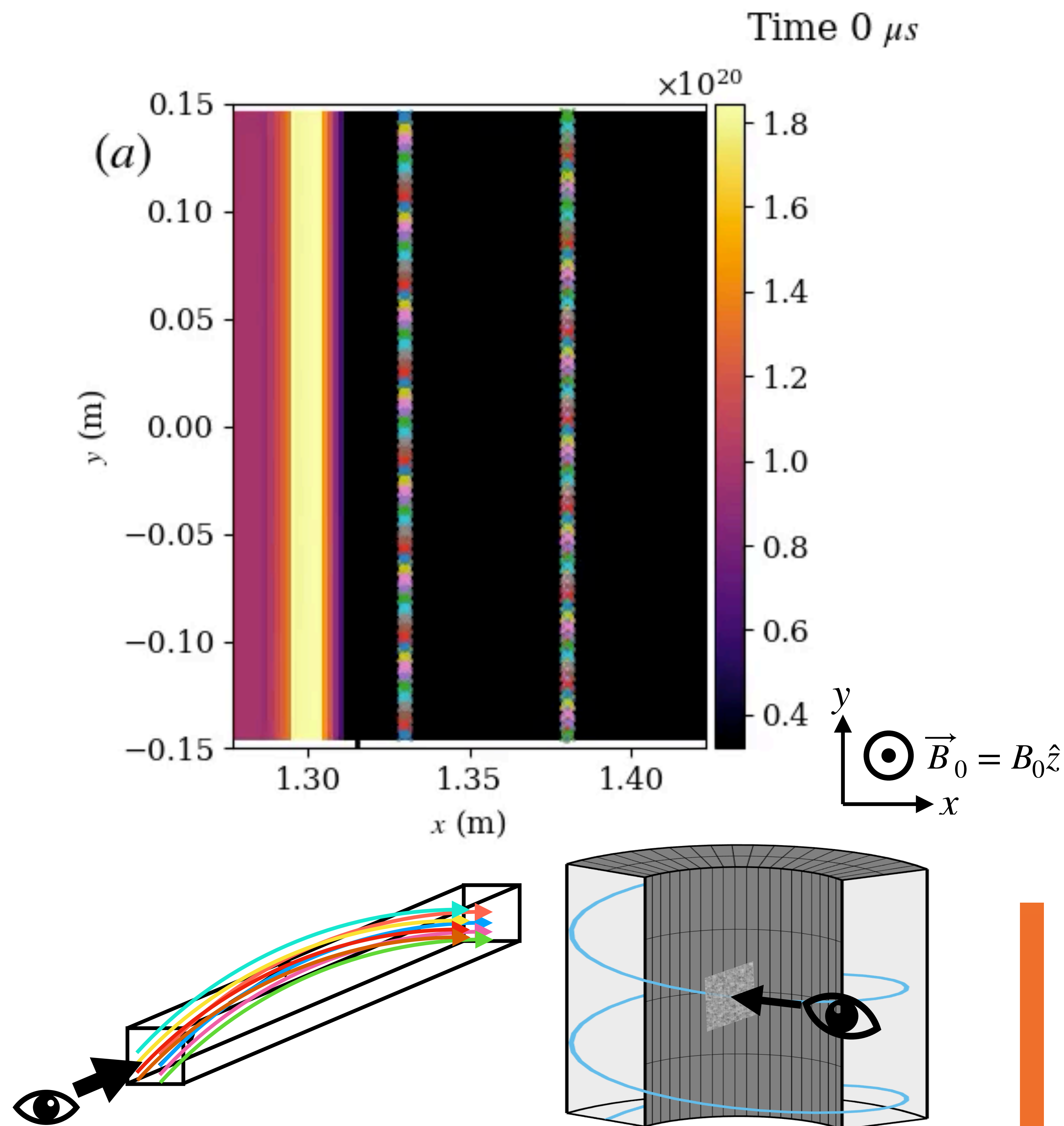

Blobs ($\beta \sim 1\,\%$) bend/stretch magnetic field lines

First EMGK simulations of SOL ✔

First EMGK simulations of SOL ✓

- We've used simple helical geometry and parameters from NSTX H-mode SOL, but with 10x n_0 to stress-test EM effects (could happen locally in ELM?)
    - Results in magnetic fluctuations $\delta B_\perp / B_0 \sim 1\,\%$
    - Gkeyll can handle this strong magnetic turbulence robustly ✓
    - Mandell et al, JPP 2020; Hakim et al, PoP 2020

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Do EM fluctuations affect SOL turbulence dynamics?

- Now going to do side-by-side comparison of electrostatic and electromagnetic cases. Things to look for:
  - Changes in the blob structures, dynamics, frequency, etc

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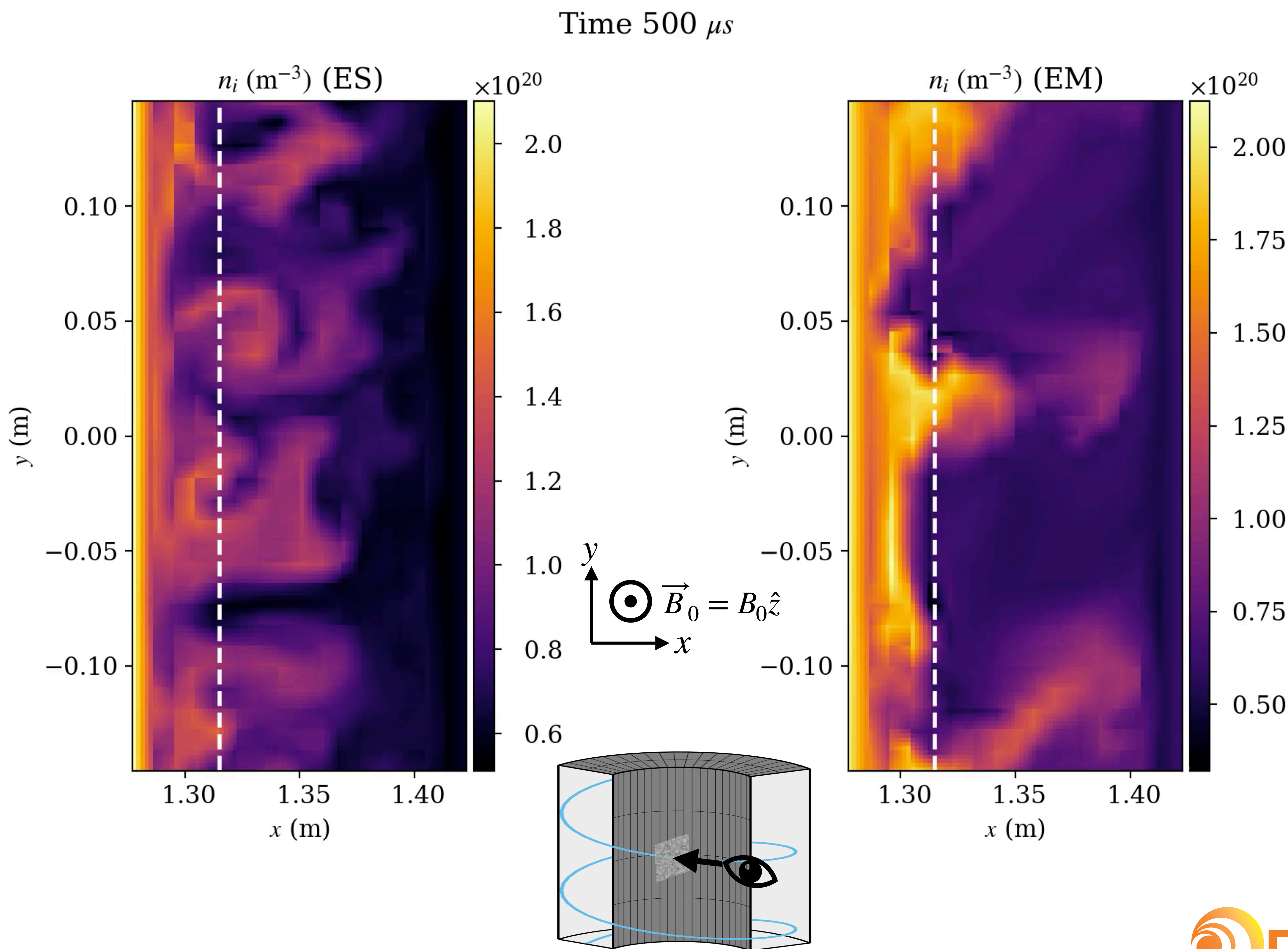
Electrostatic/electromagnetic comparison: midplane ion density



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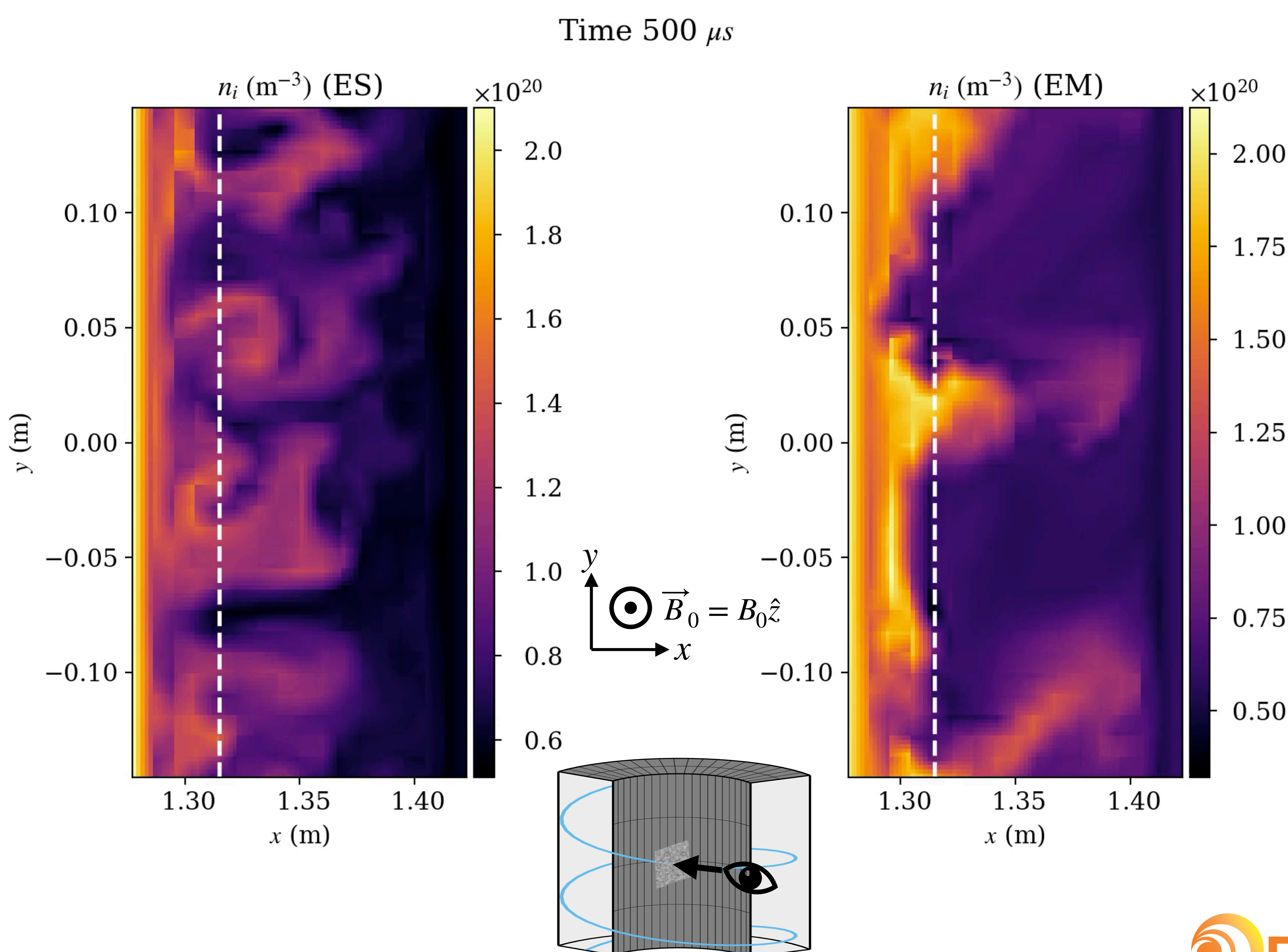
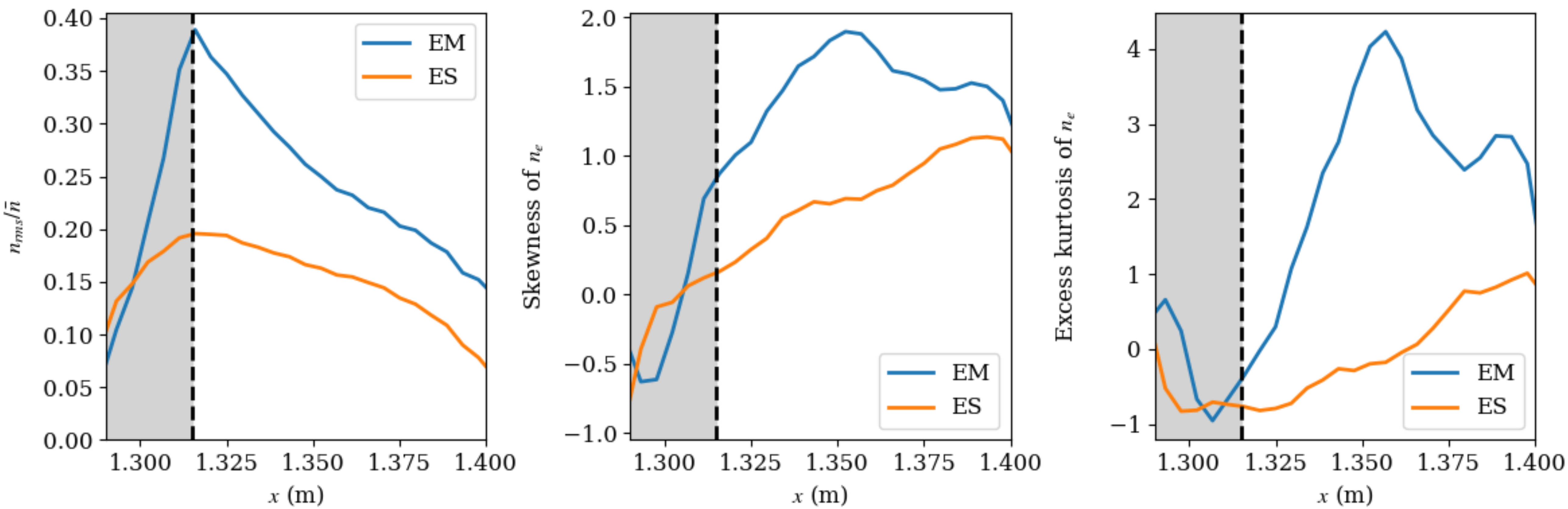


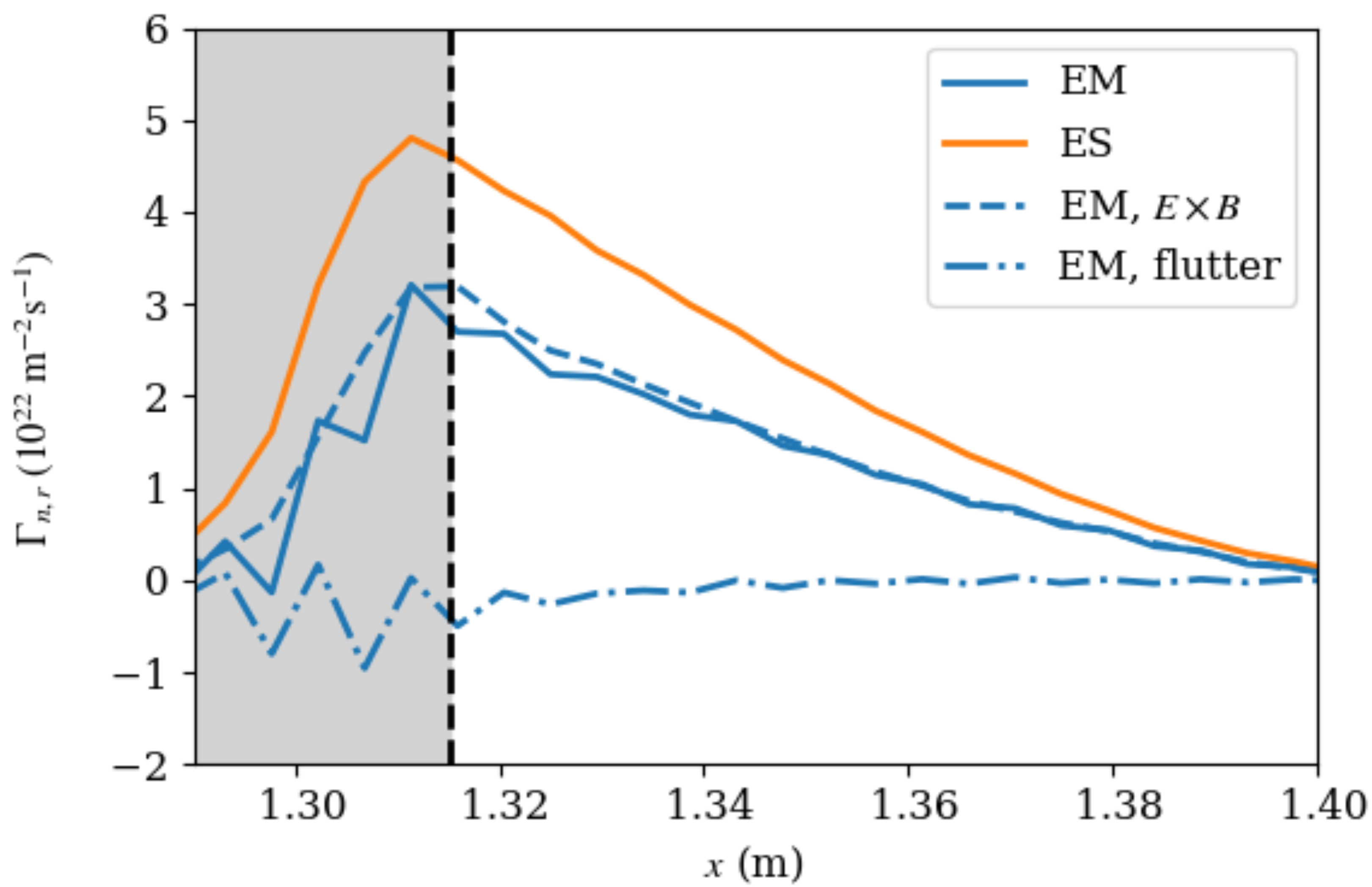
Electrostatic/electromagnetic comparison: density fluctuations statistics



EM has larger, more intermittent density fluctuations

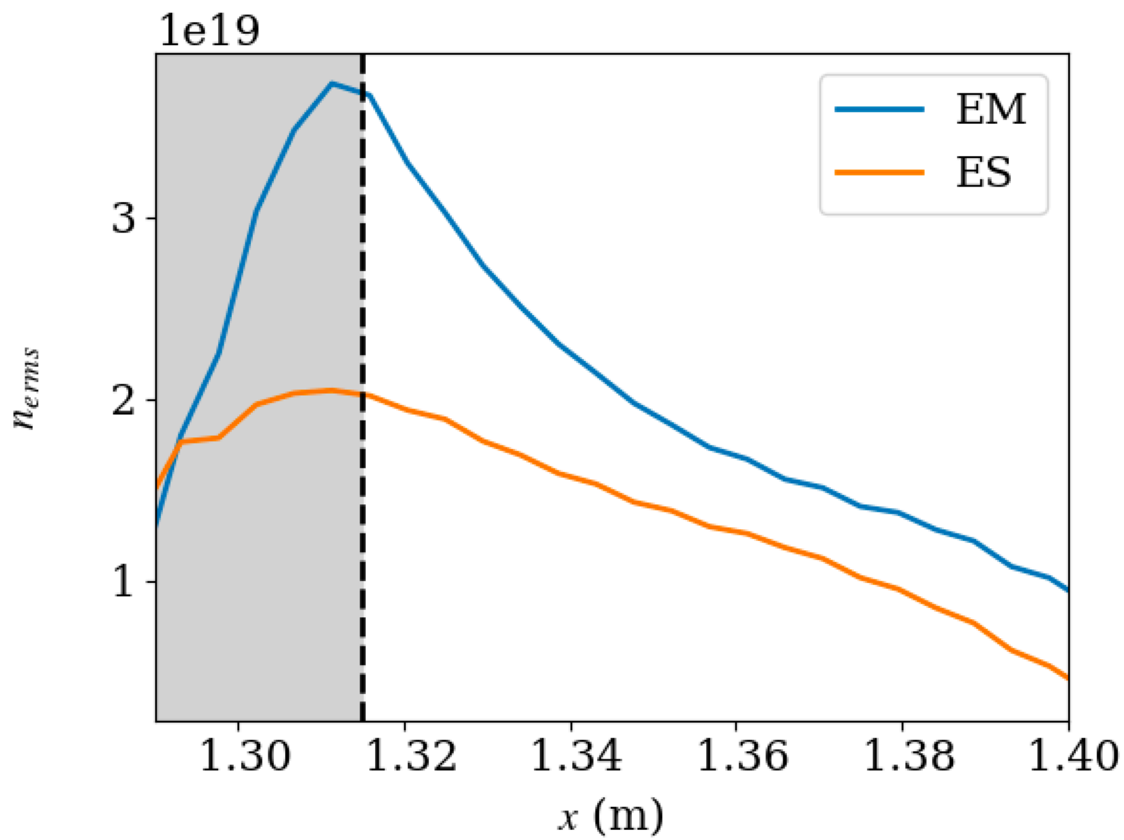
Electrostatic/electromagnetic comparison: radial particle flux (near midplane)

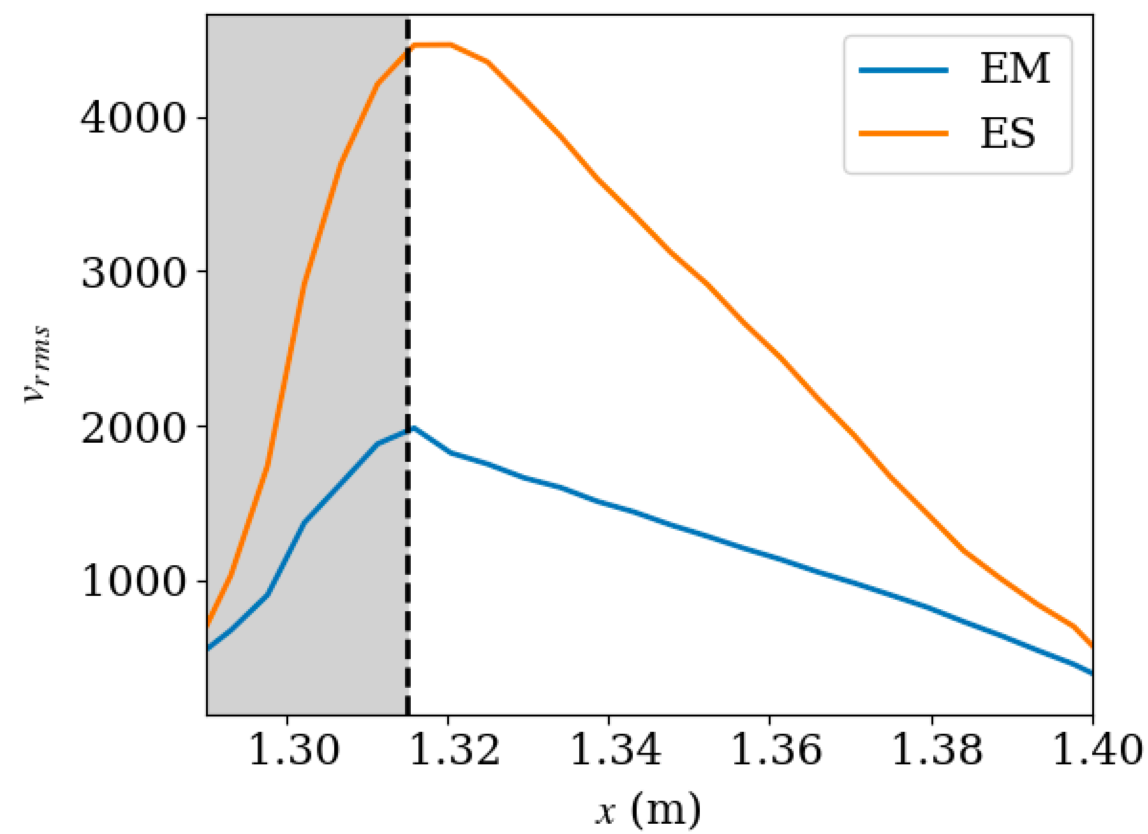
- Might expect larger density fluctuations means more transport, but…



Radial particle transport reduced in EM case by ~ 40%

Electrostatic/electromagnetic comparison: radial particle flux (near midplane)

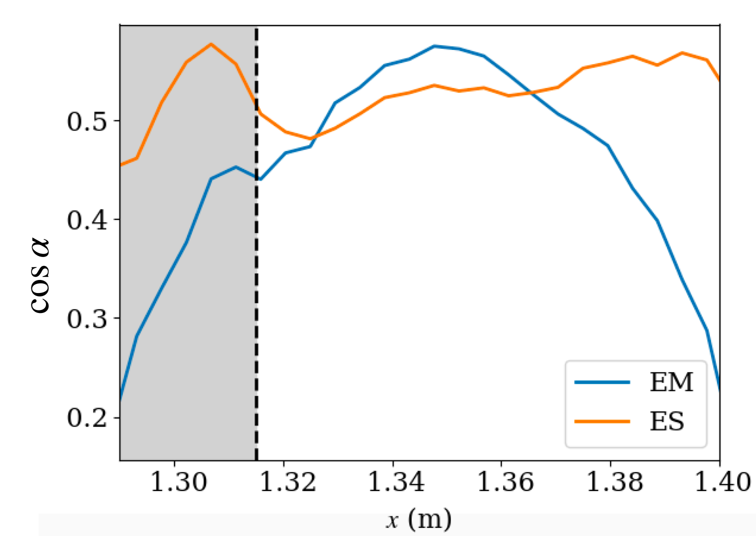




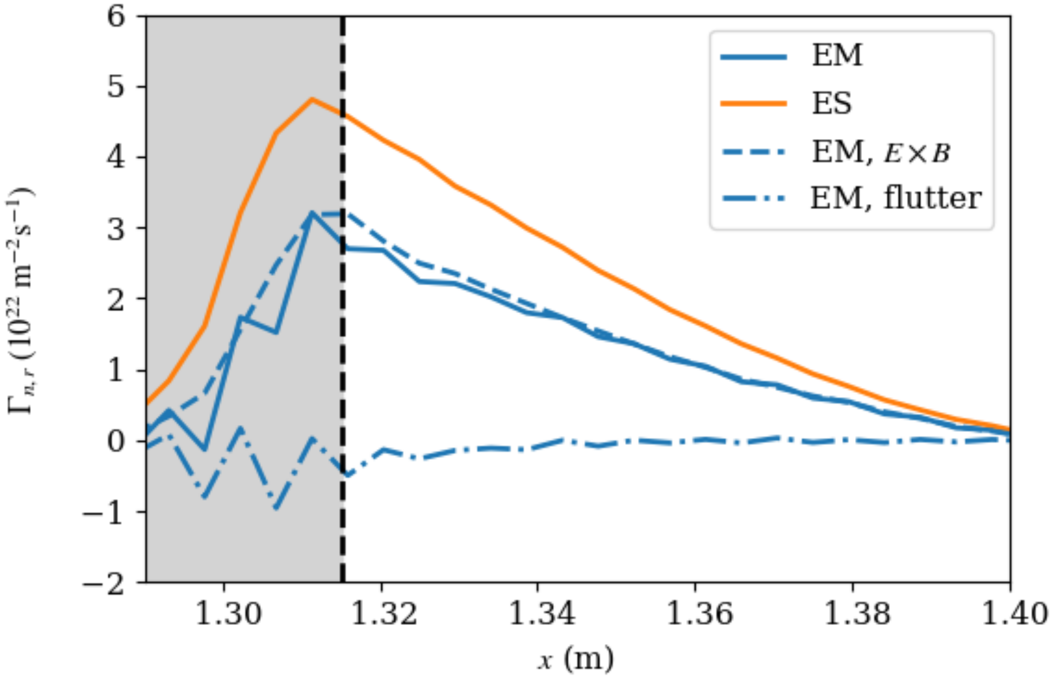
The radial $E \times B$ particle flux is defined as

$$\Gamma_r = \langle \tilde{n}_e \tilde{v}_r \rangle = n_{e,rms} v_{r,rms} \cos \alpha$$

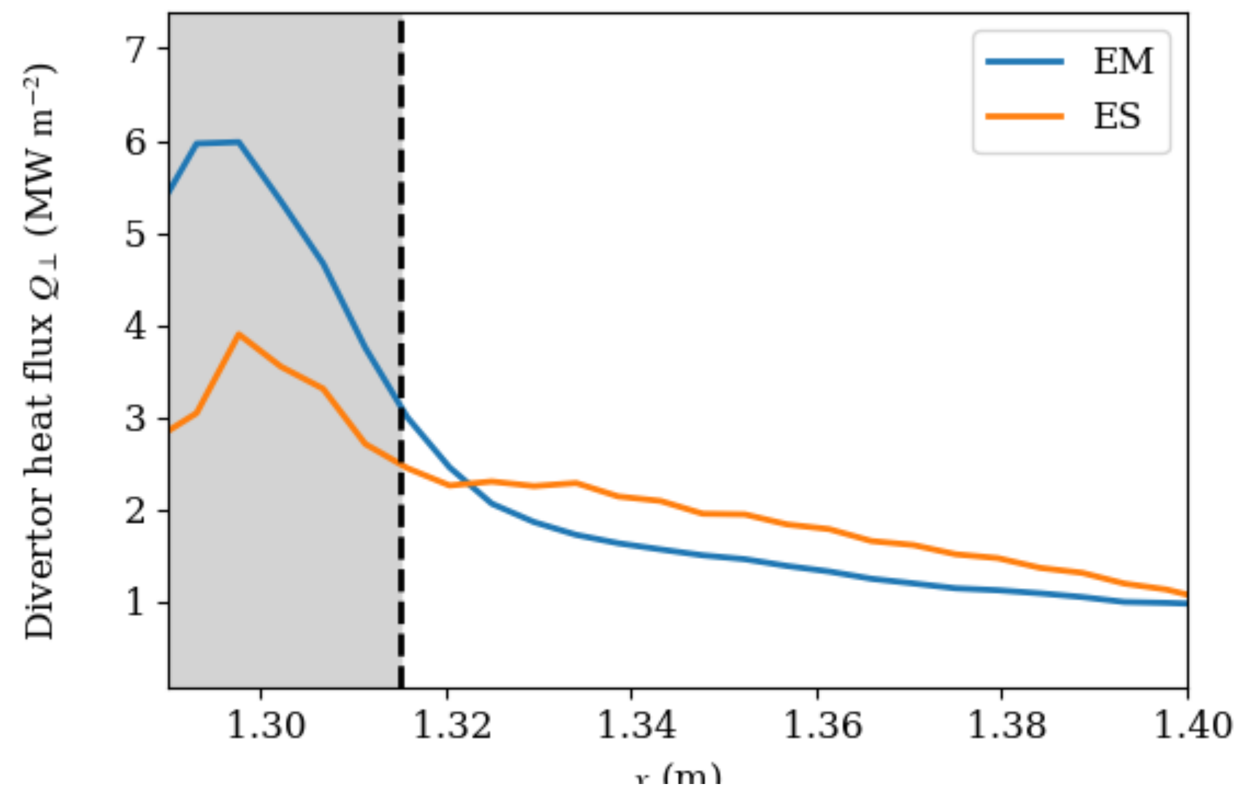
In this case, using n_{rms} as a surrogate diagnostic for transport is not sufficient!



Electrostatic/electromagnetic comparison: divertor heat flux profile



$\Rightarrow$



- Because EM case has less radial transport, heat flux to divertor is more peaked in EM case
- ES case over-predicts transport, over-predicts heat flux width

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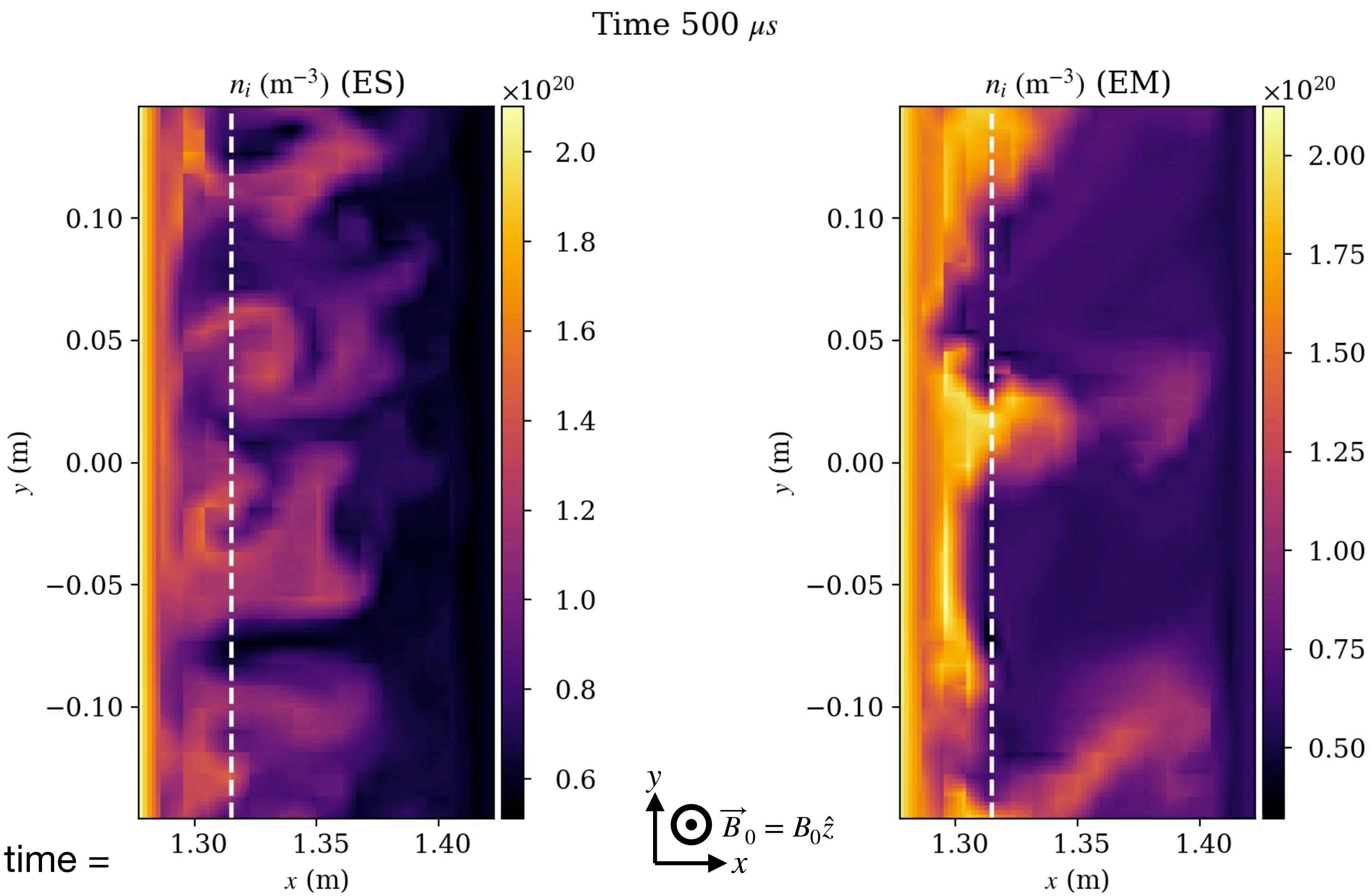
Modest simulation cost (even for EM!)

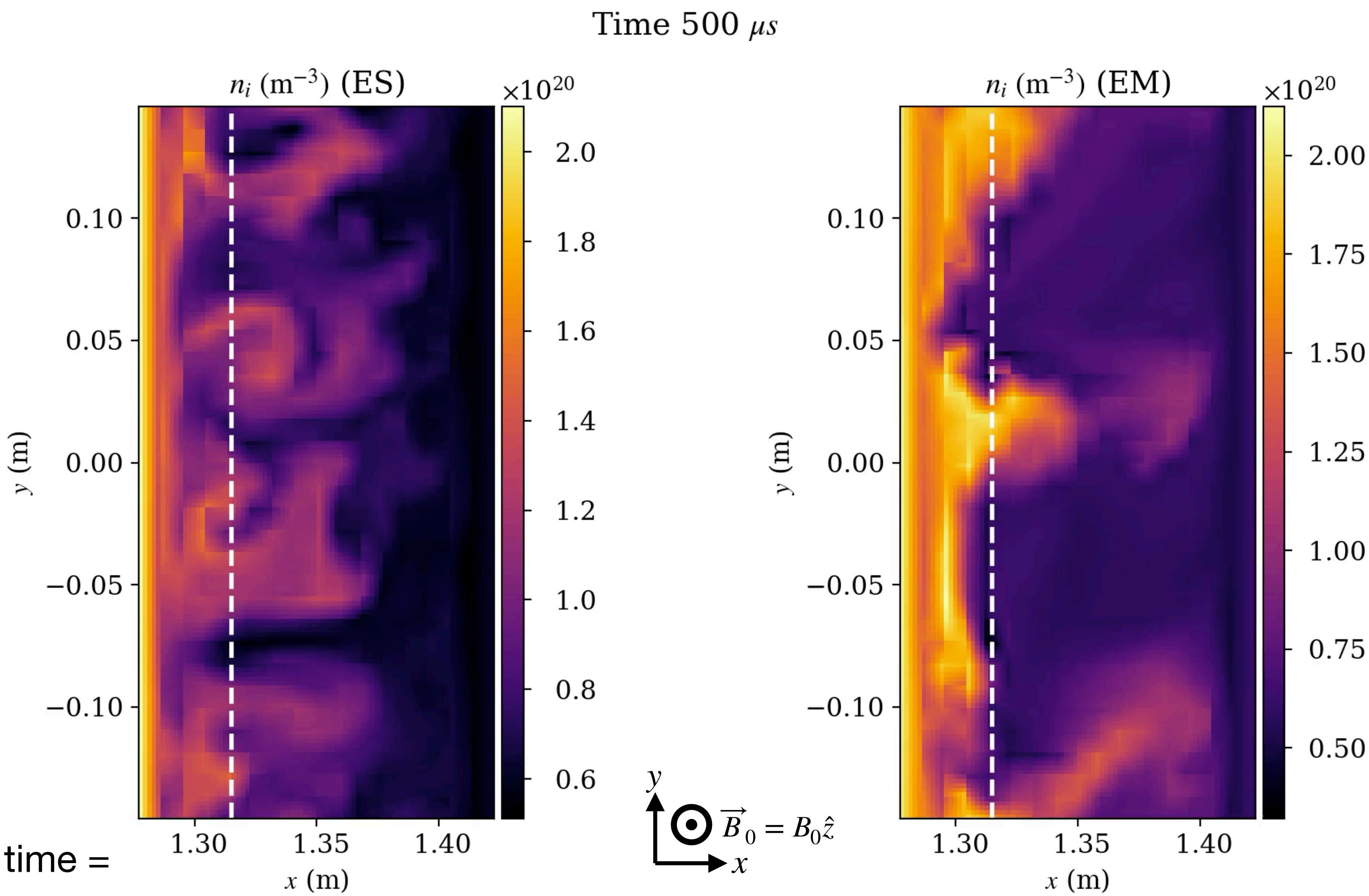


Total simulation time = 1 ms ~ 20 ion transit times

(Nx, Ny, Nz, Nv, Nm) ~(32, 64, 20, 20, 10)	Electrostatic	Electromagnetic
Total wall-clock time (128 cores)	2.7 days	3.4 days
Time/timestep (wall-clock)	0.41 s	0.68 s

only ~25% more

Modest simulation cost (even for EM!)



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Towards more realistic SOL geometry

- We know magnetic shear can be important in SOL, especially near X point
- All Gkeyll results to date (NSTX and Helimak) have used simplified helical geometry
  - Neglected most geometrical factors, no magnetic shear
- Even in SMT configuration (e.g. Helimak) with const vertical field, there should be some magnetic shear because toroidal field $\sim 1/R$

$$\mathbf{B} = \frac{B_0 R_0}{R}\hat{\boldsymbol{\varphi}} + B_v \hat{\mathbf{Z}}, \qquad q(R) = \frac{HB_\varphi}{2\pi R B_v} = \frac{B_0 R_0 H}{2\pi R^2 B_v}, \qquad \hat{s} = \frac{R}{q}\frac{dq}{dR} = -2$$

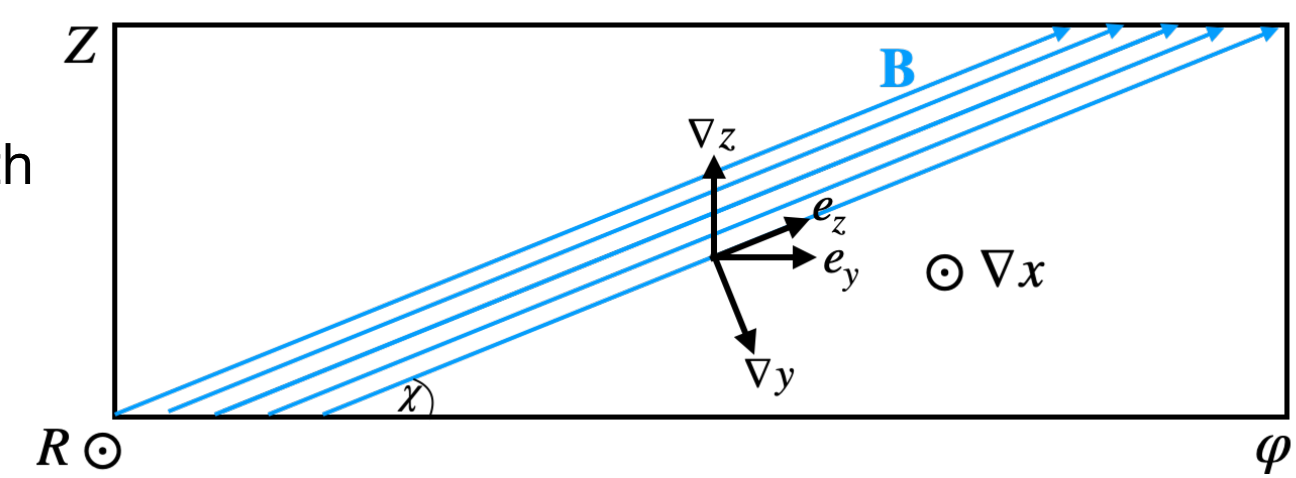
- Keeping helical configuration, can adjust shear by making $B_v = B_v(R) = B_{v0}(R/x_0)^n$, so that

$$\hat{s} = -2 - \frac{R}{B_v}\frac{dB_v}{dR} = -2 - n$$

- Take field-aligned helical coordinate system with

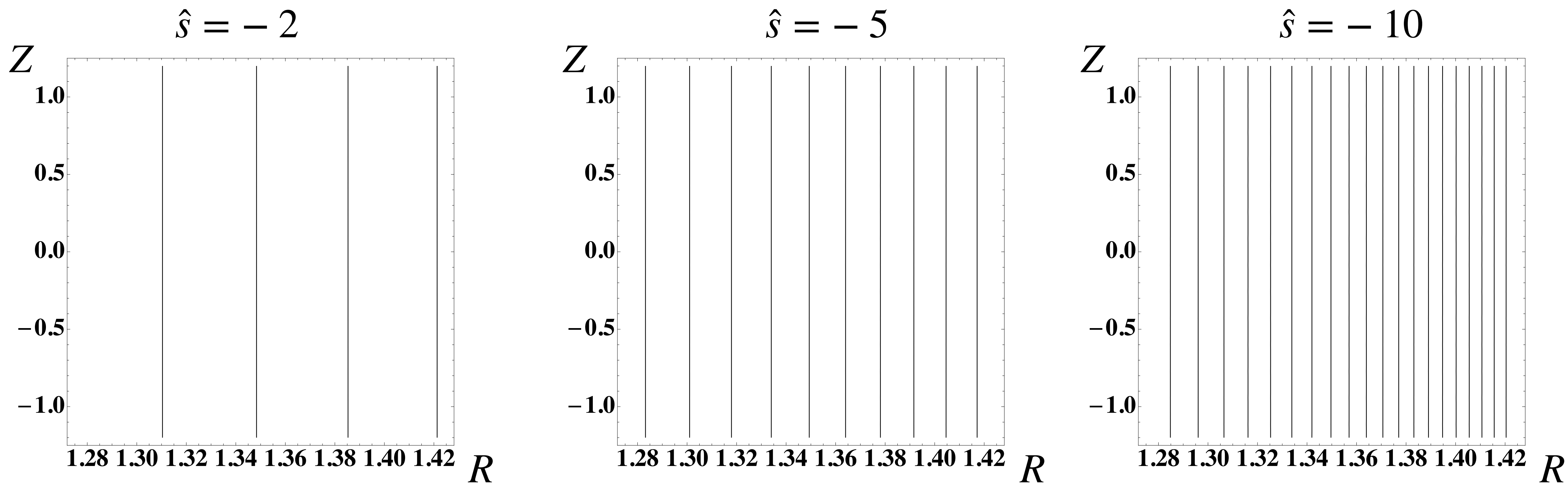
$$x = R, \qquad z = Z, \qquad y = x_0\left(\varphi - \frac{2\pi q Z}{H}\right),$$

$$\mathbf{B} = \frac{RB_v}{x_0}\nabla x \times \nabla y$$

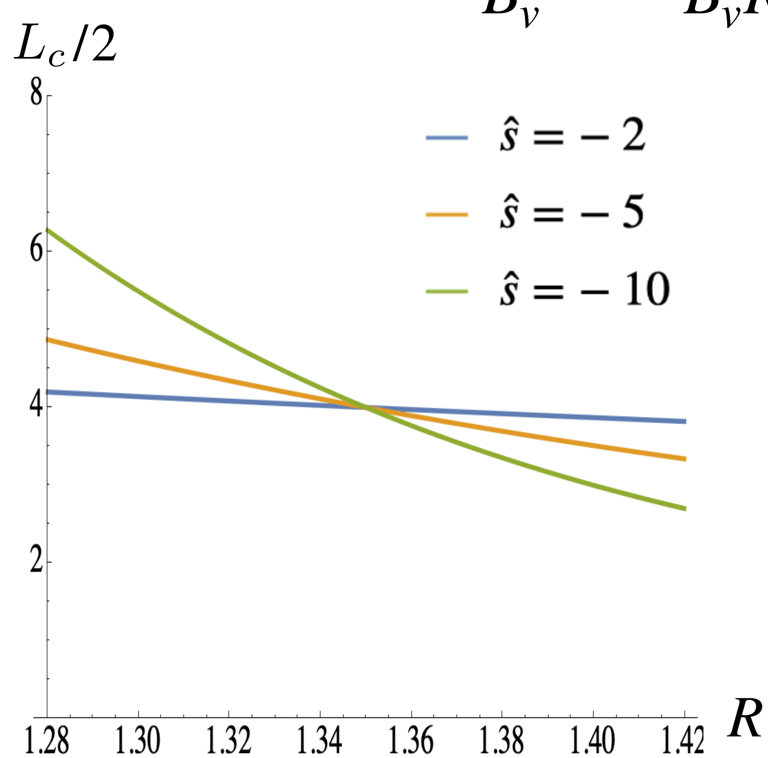


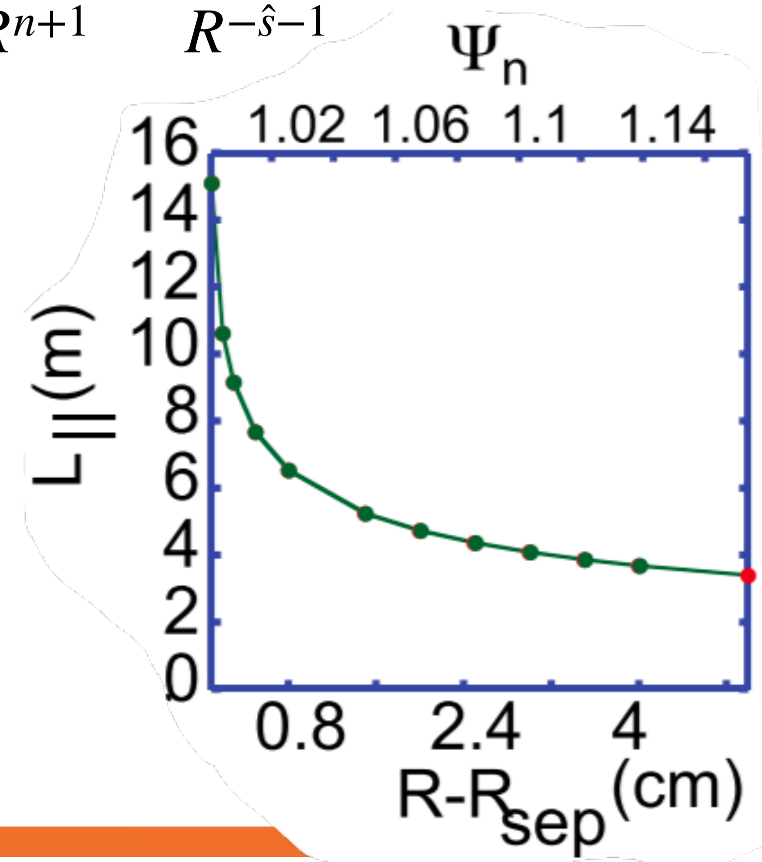
Helical geometry with magnetic shear

Vertical (~poloidal) flux: $\Psi(R, Z) = R^2 B_v / 2 \sim R^{-\hat{s}}$



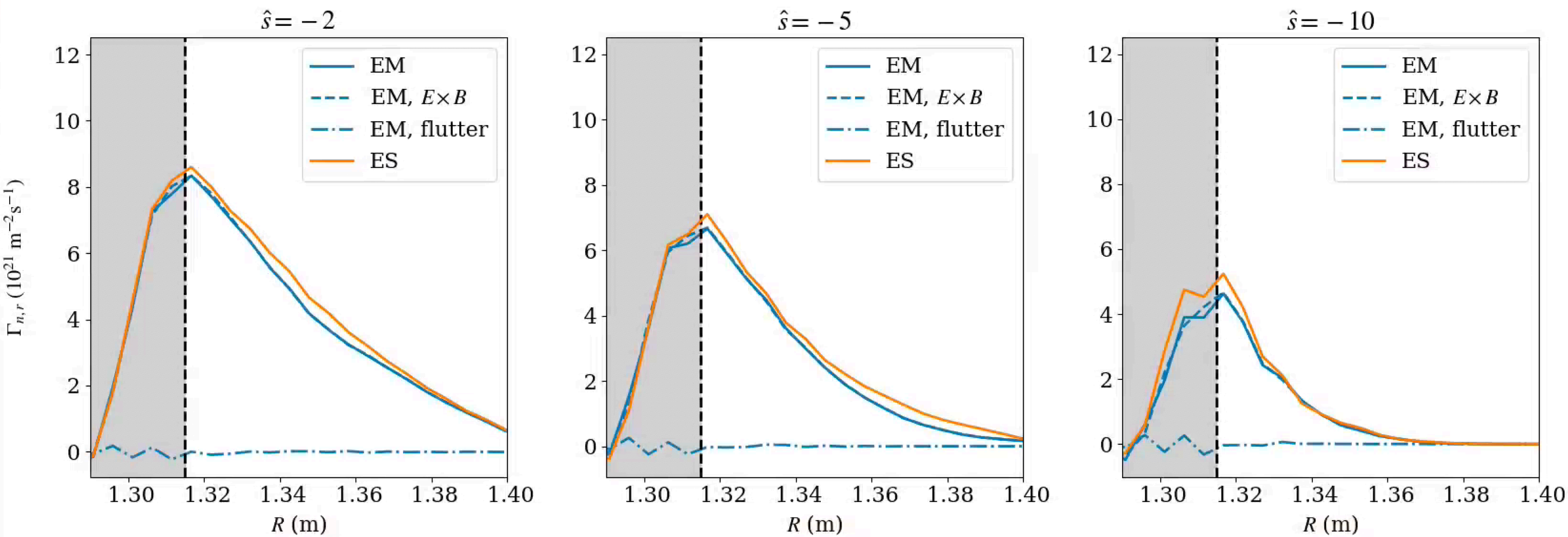
Connection length: $L_c = \frac{HB}{B_v} \approx \frac{HB_0 R_0}{B_v R} \sim \frac{1}{R^{n+1}} \sim \frac{1}{R^{-\hat{s}-1}}$





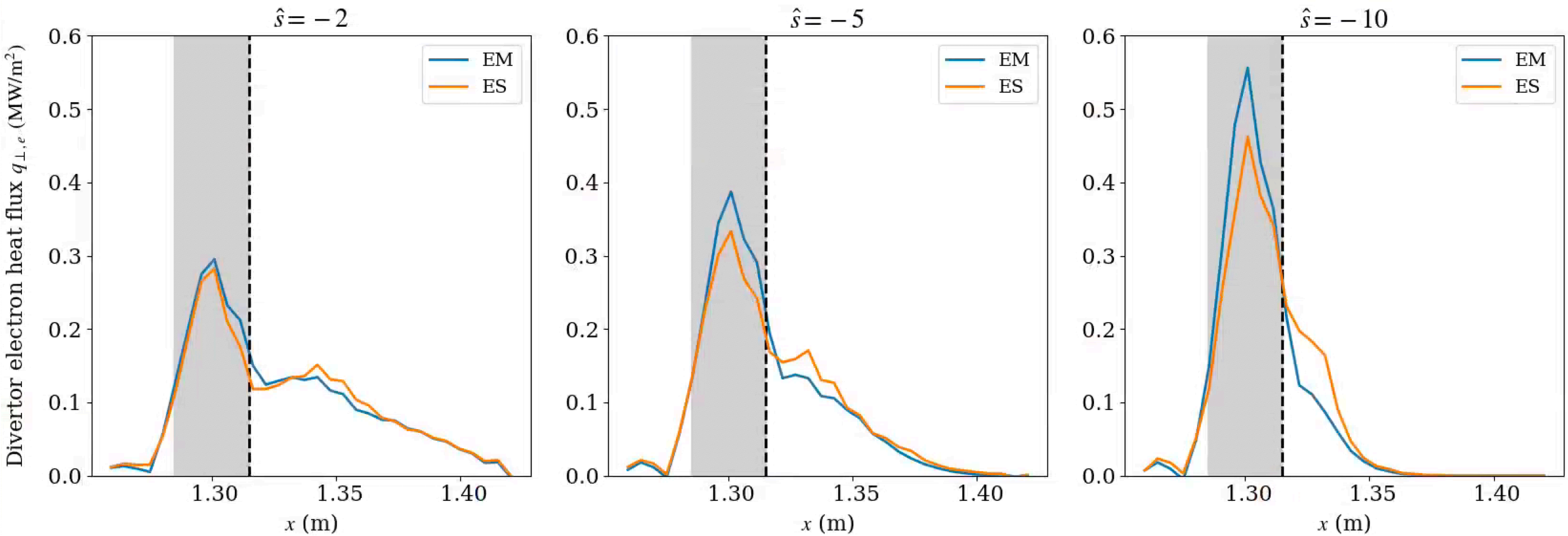
NSTX SOL connection length Boedo et al, PoP 2014

$\hat{s}$ scan: radial particle flux (near midplane)



- Transport decreases as $|\hat{s}|$ increases
- EM cases again have less transport
- This is at ~ experimental $\beta \sim 0.1\,\%$ (no more 10x)

$\hat{s}$ scan: divertor heat flux profiles



- Heat flux profile gets narrower as $|\hat{s}|$ increases
- EM effects more important as $|\hat{s}|$ increases

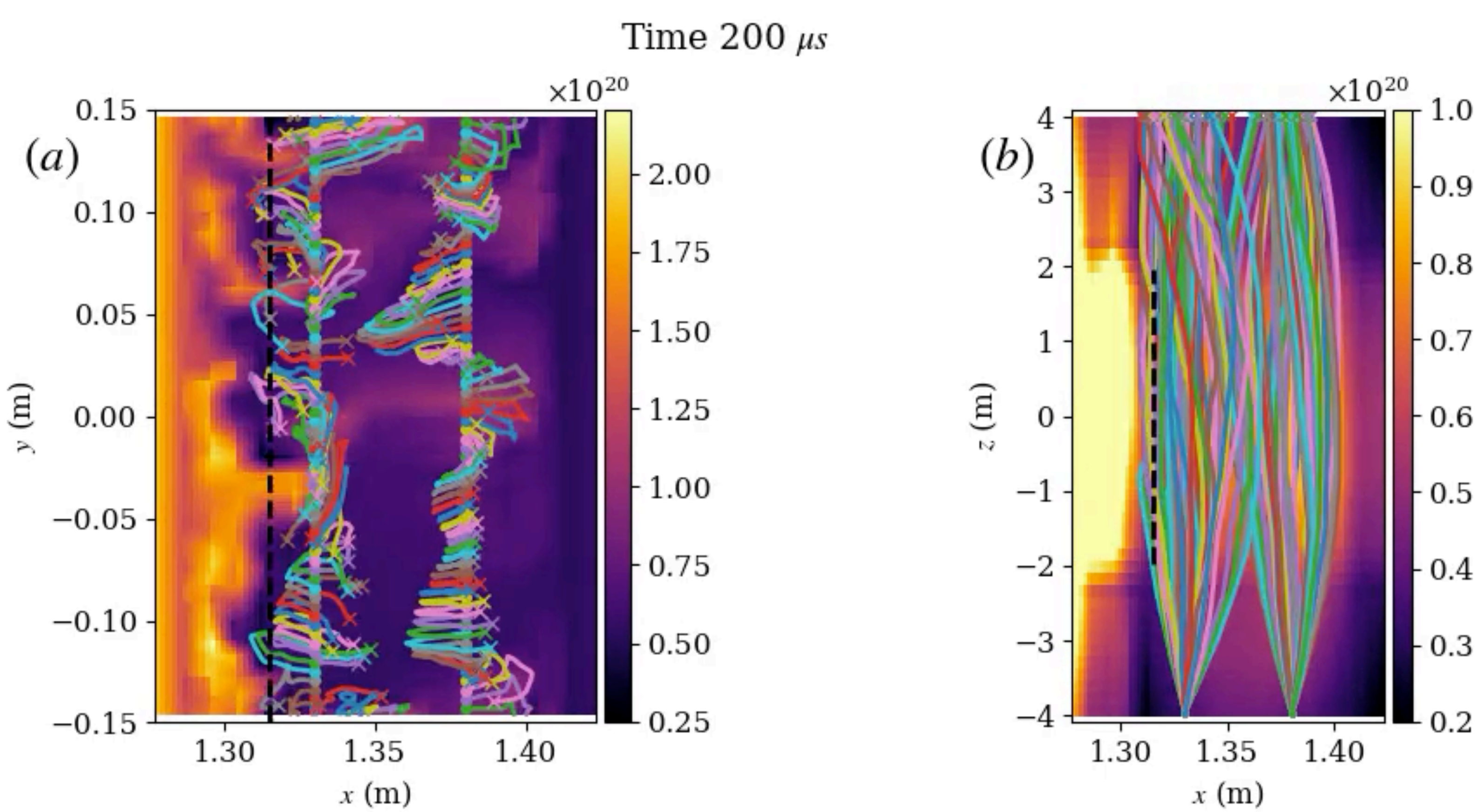
Summary

- Gkeyll is being used to study SOL turbulence in tokamaks like NSTX (only handles open field lines right now)

- Gkeyll has produced the first nonlinear electromagnetic gyrokinetic simulations in the SOL, can handle strong magnetic turbulence with $\delta B_{\perp}/B_0 \sim 1\,\%$

- In high β regime, including electromagnetic fluctuations results in larger, more intermittent fluctuations in SOL but less transport

- Moving towards more realistic SOL geometry, including magnetic shear



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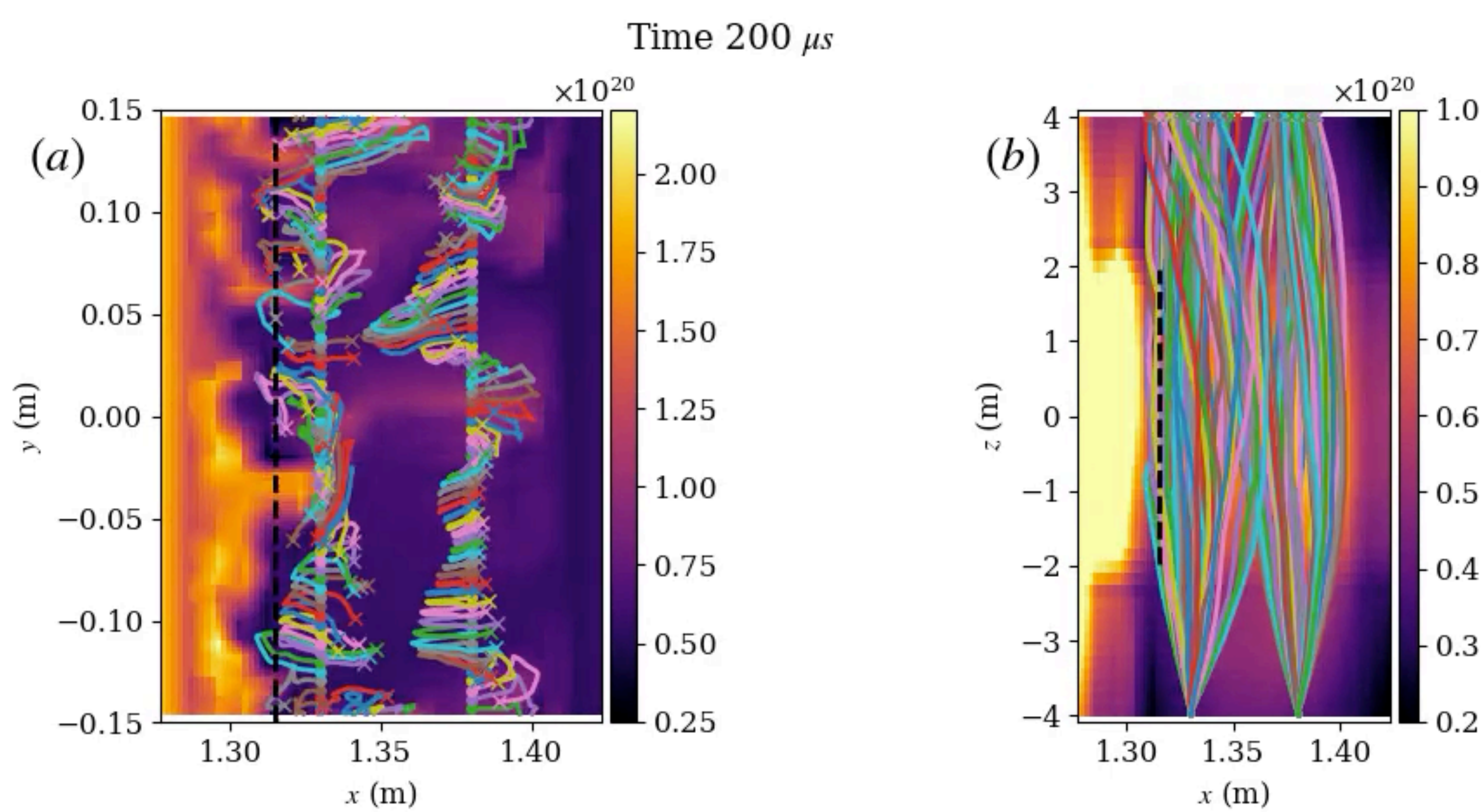

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Acknowledgements

Gkeyll team:

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Petr Cagas
Mana Francisquez
Jimmy Juno
Rupak Mukherjee
Liang Wang
Eric Shi
… and others!

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PRINCETON UNIVERSITY

DOE CSGF

https://github.com/ammarhakim/gkyl/

https://gkeyll.readthedocs.io

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E. L. Shi et al, Phys. Plasmas 26 (1) (2019) 012307

T. Bernard et al, Phys. Plasmas 26 (4) (2019) 042301

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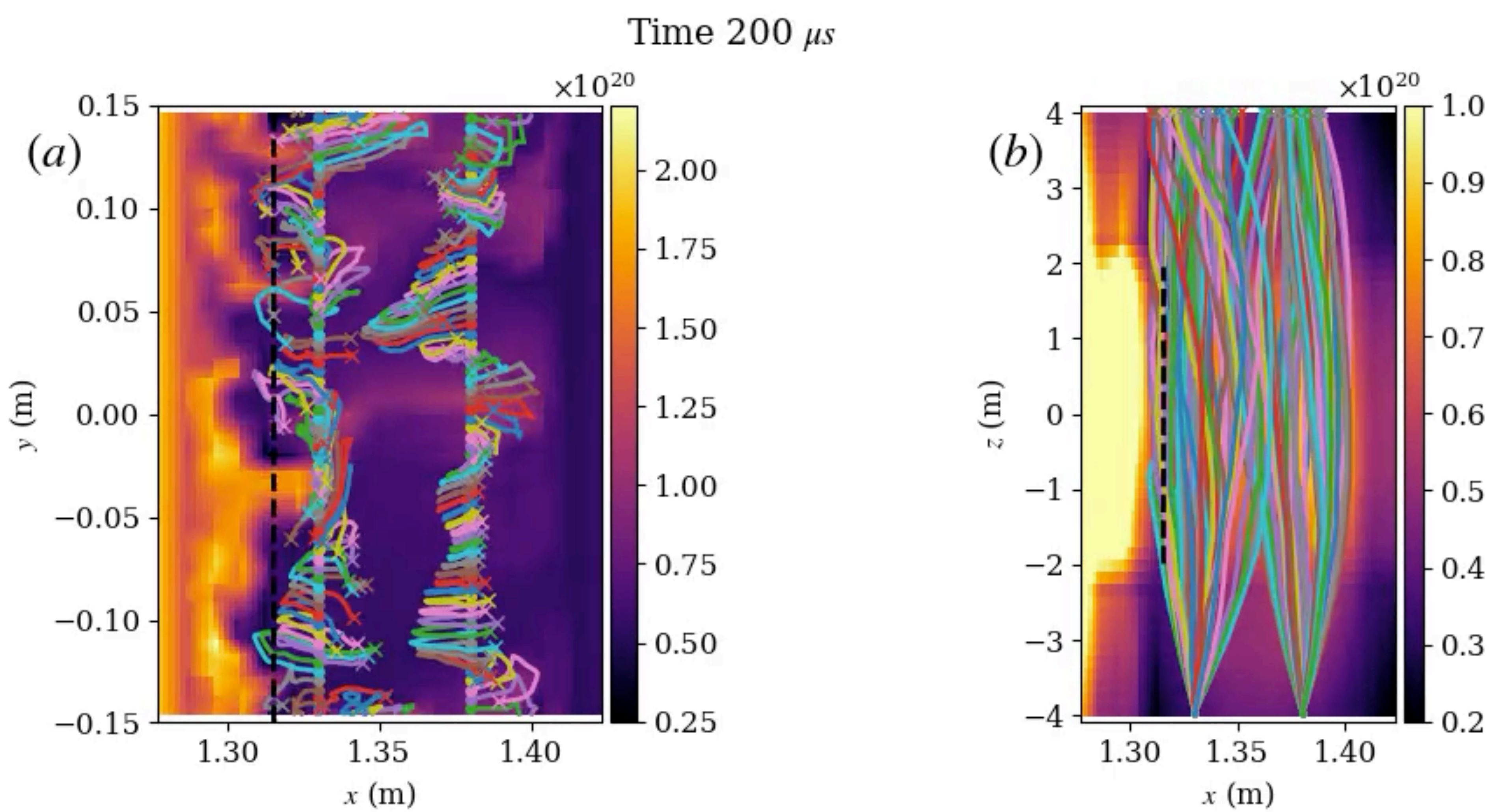

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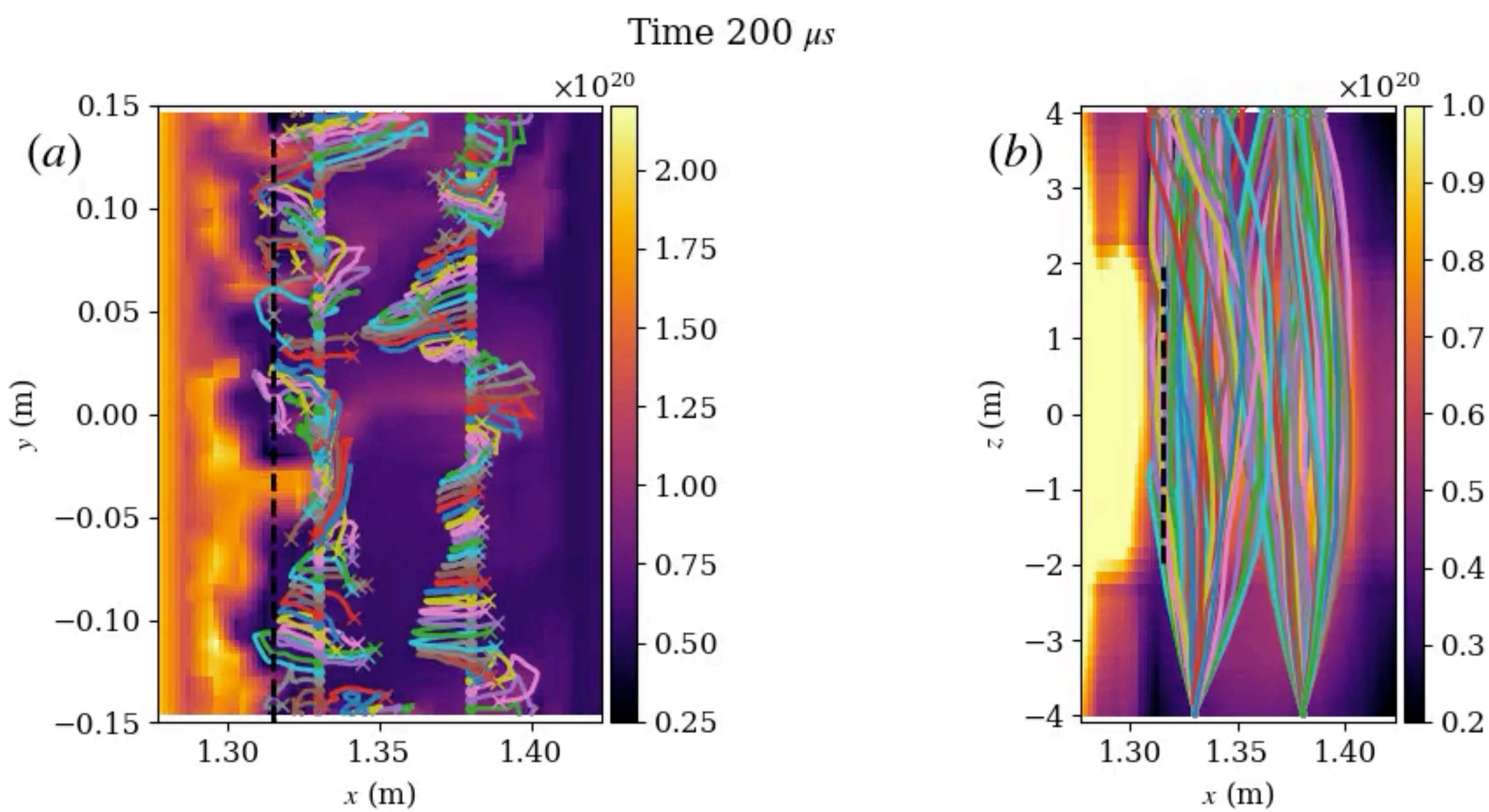
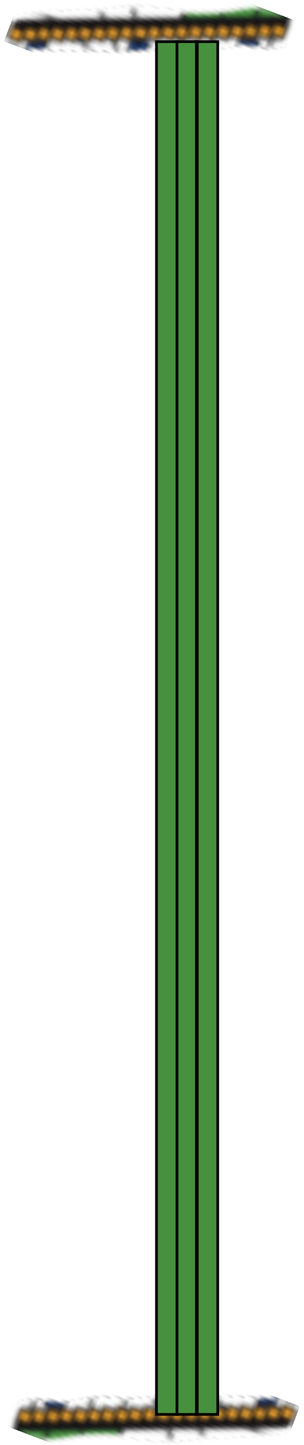
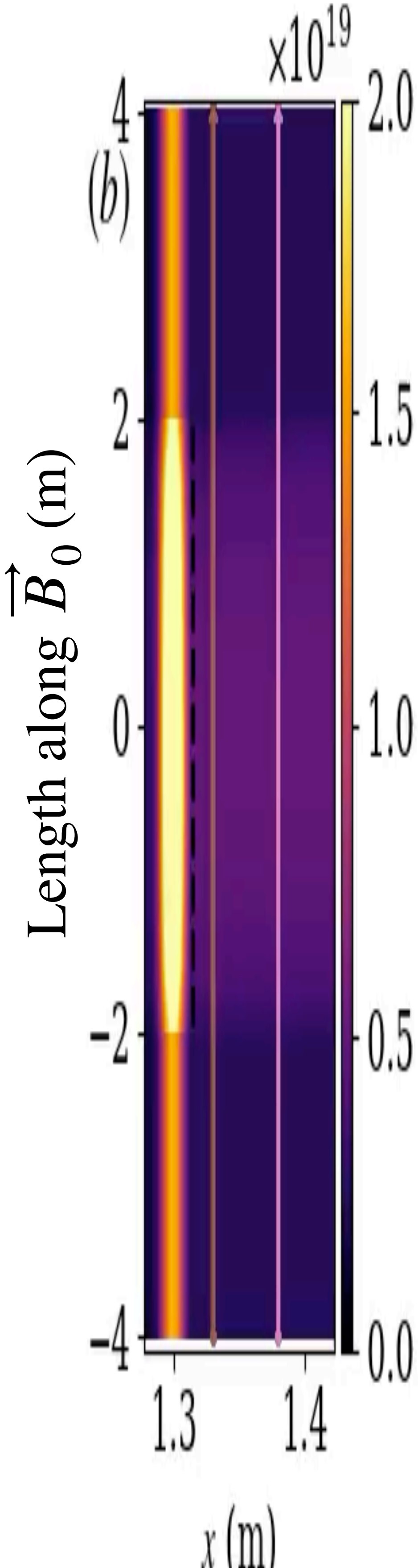


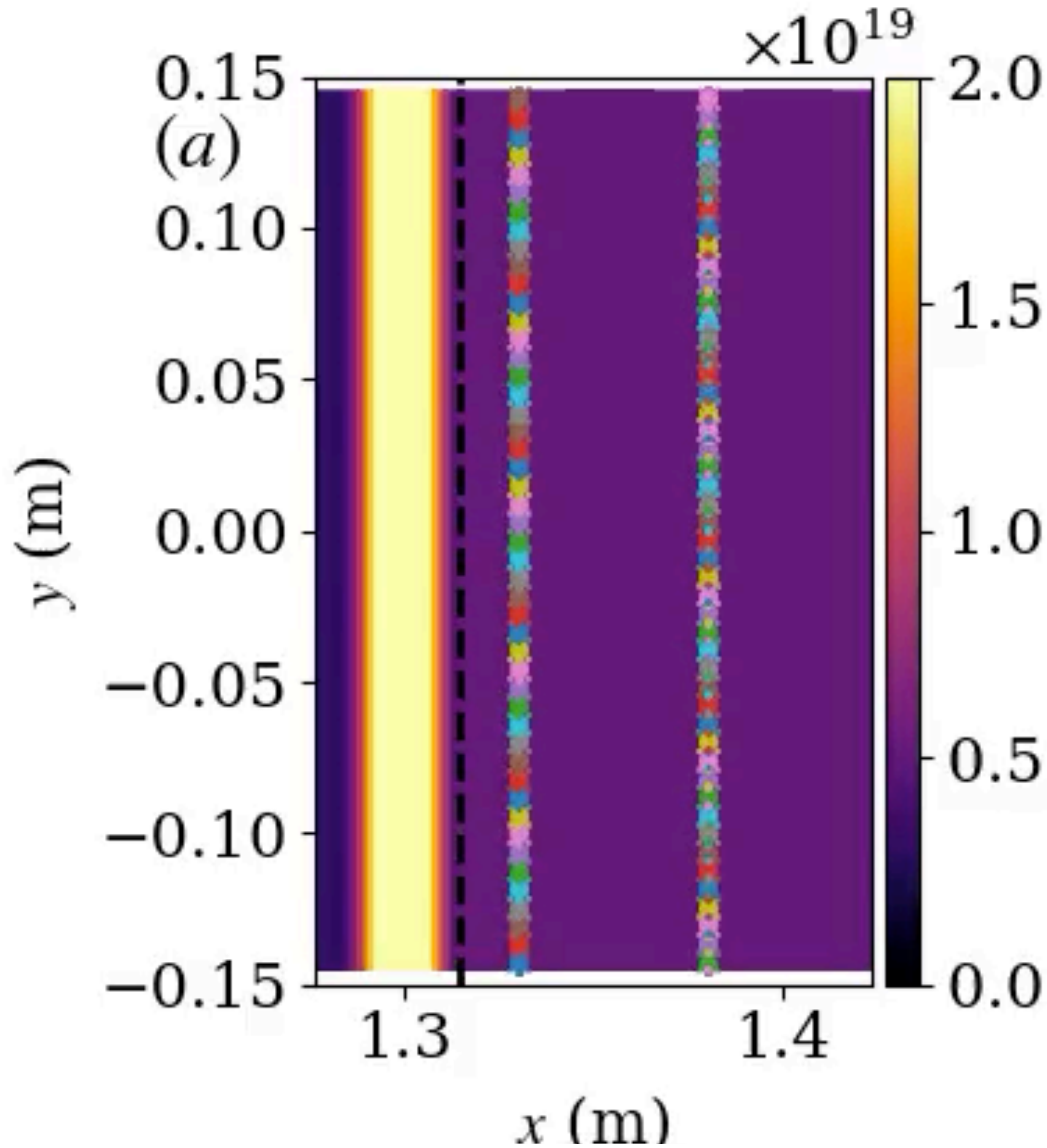
Back-up slides

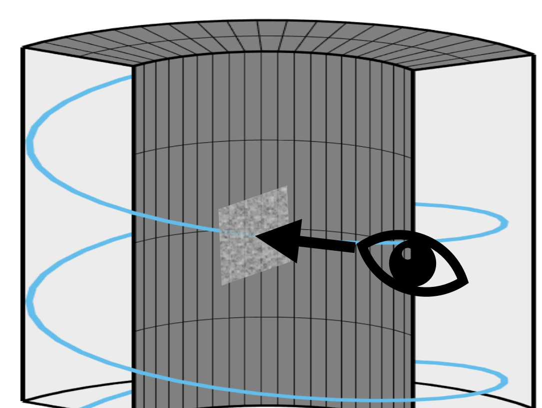
Dancing field lines at ~ experimental β

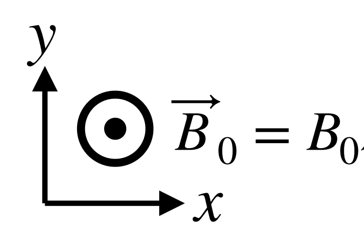
Time 0 μs











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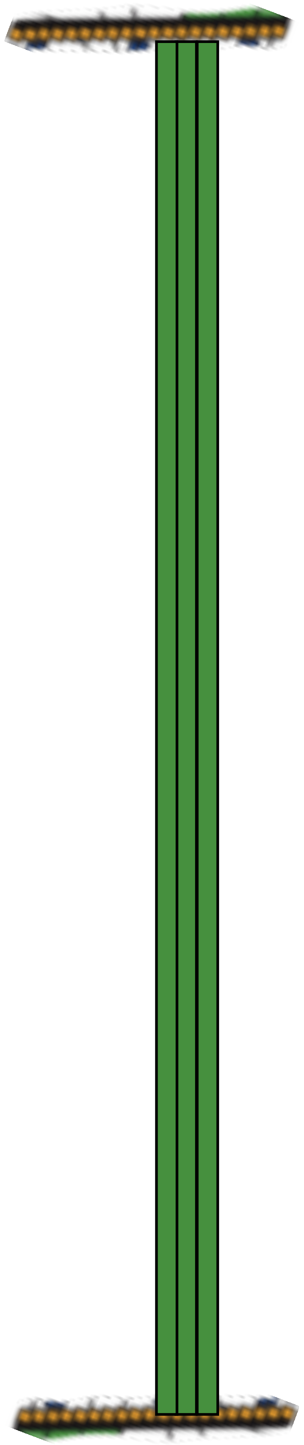

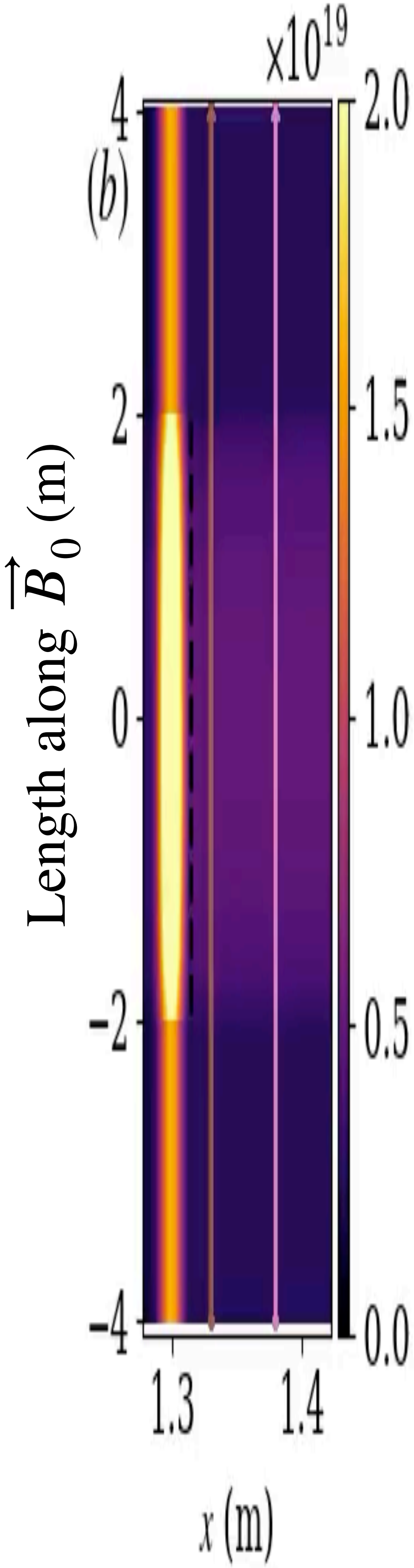

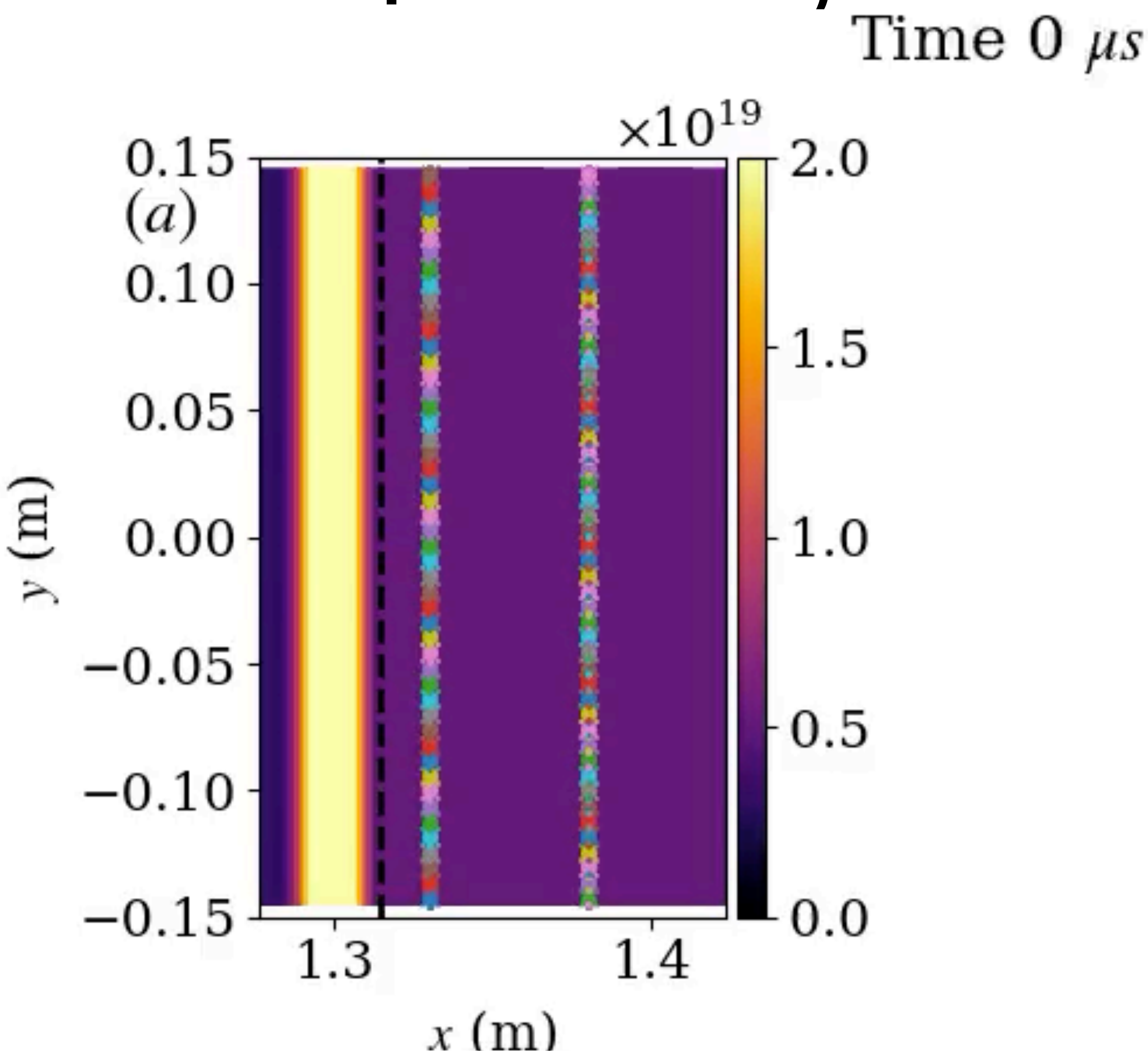

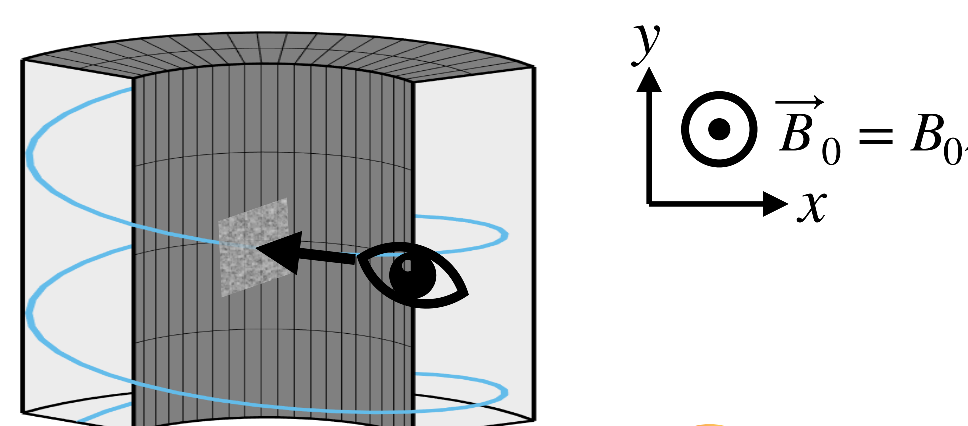

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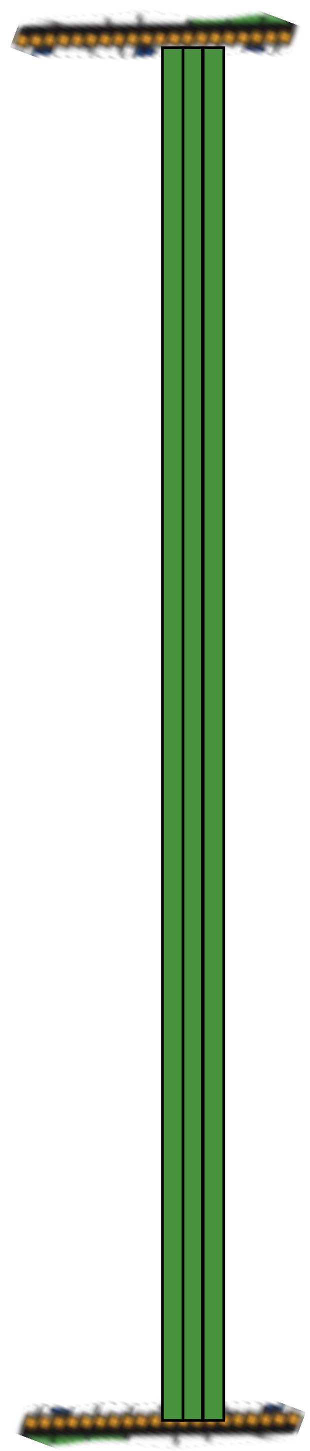
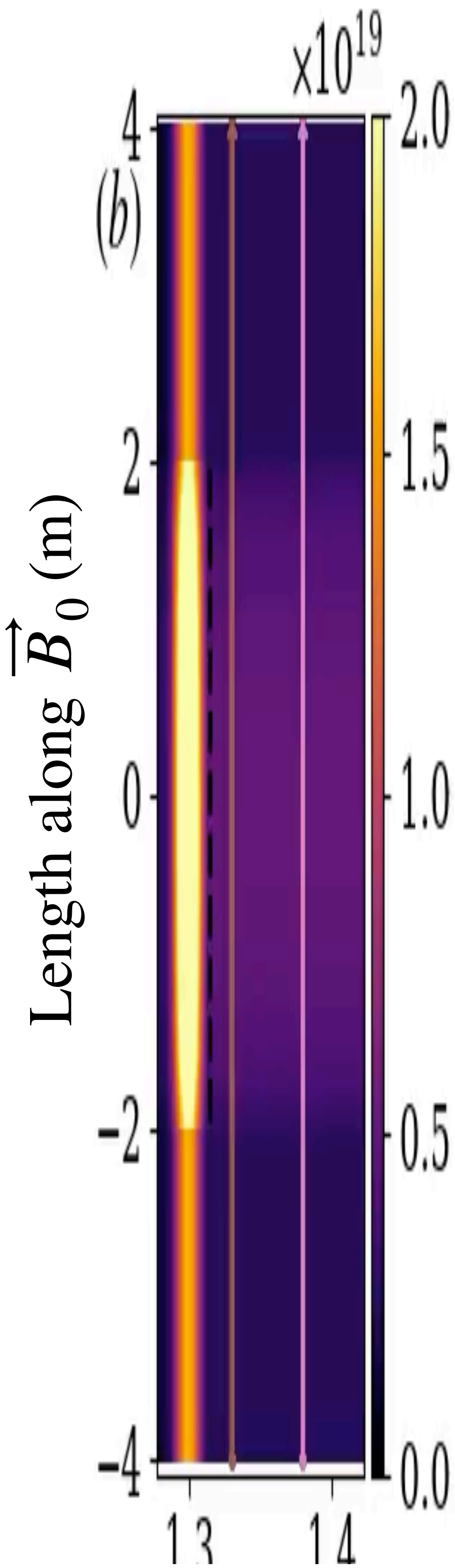
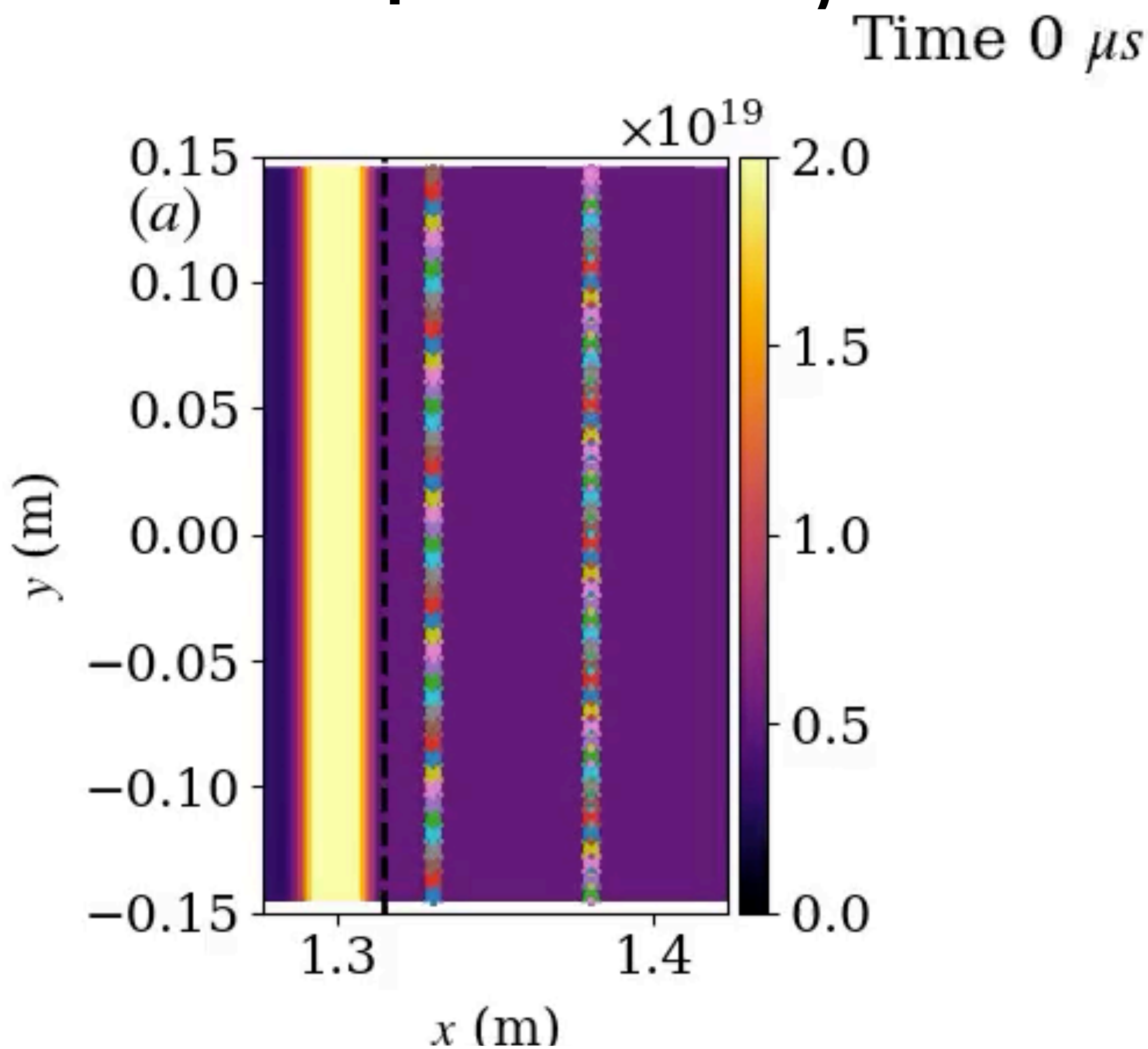
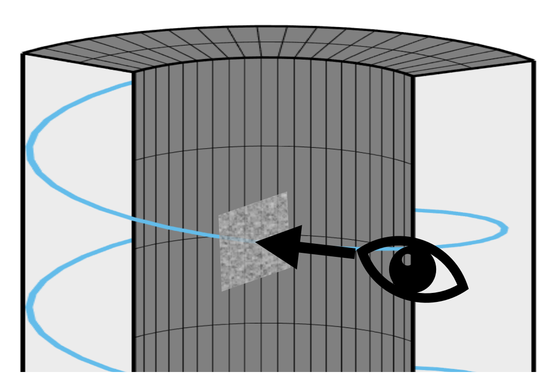
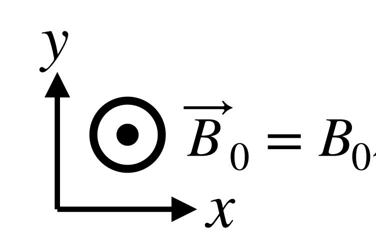




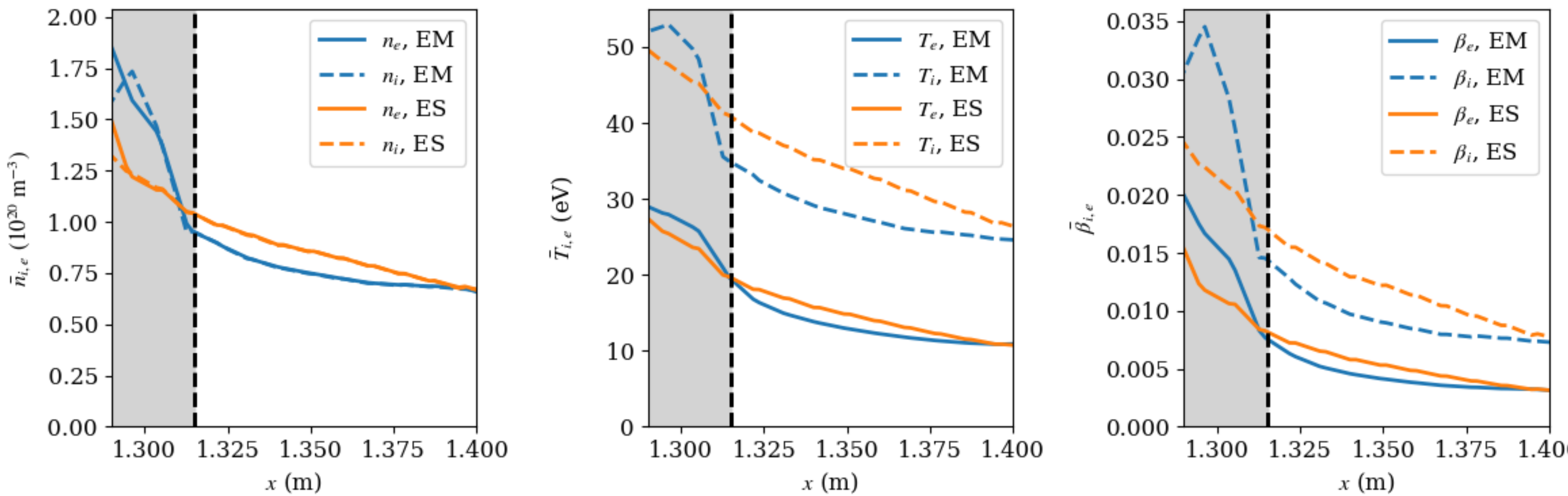






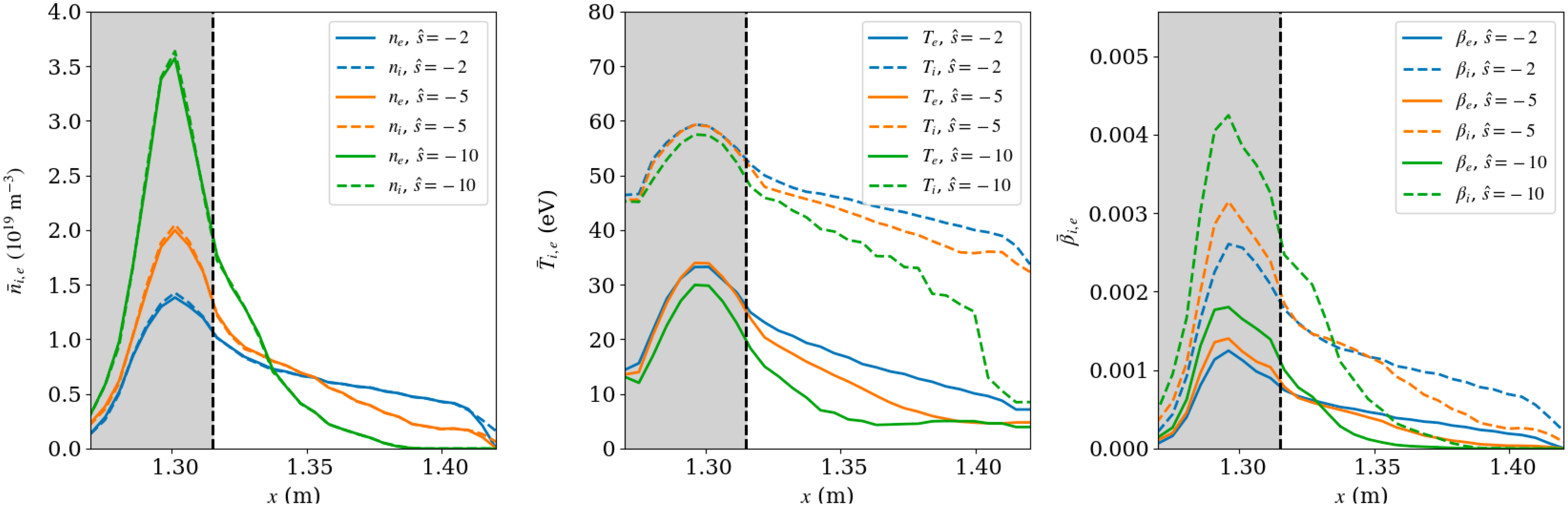
But increasing connection length, adding magnetic shear can also increase magnetic fluctuations and affect transport

Electrostatic/electromagnetic comparison: midplane profiles



- $\beta_e \sim 0.5\,\%$, $\beta_i \sim 1\,\%$ in SOL region ($\sim 10\times$ NSTX SOL)
- Profiles are steeper in source region, shallower in SOL region in EM case

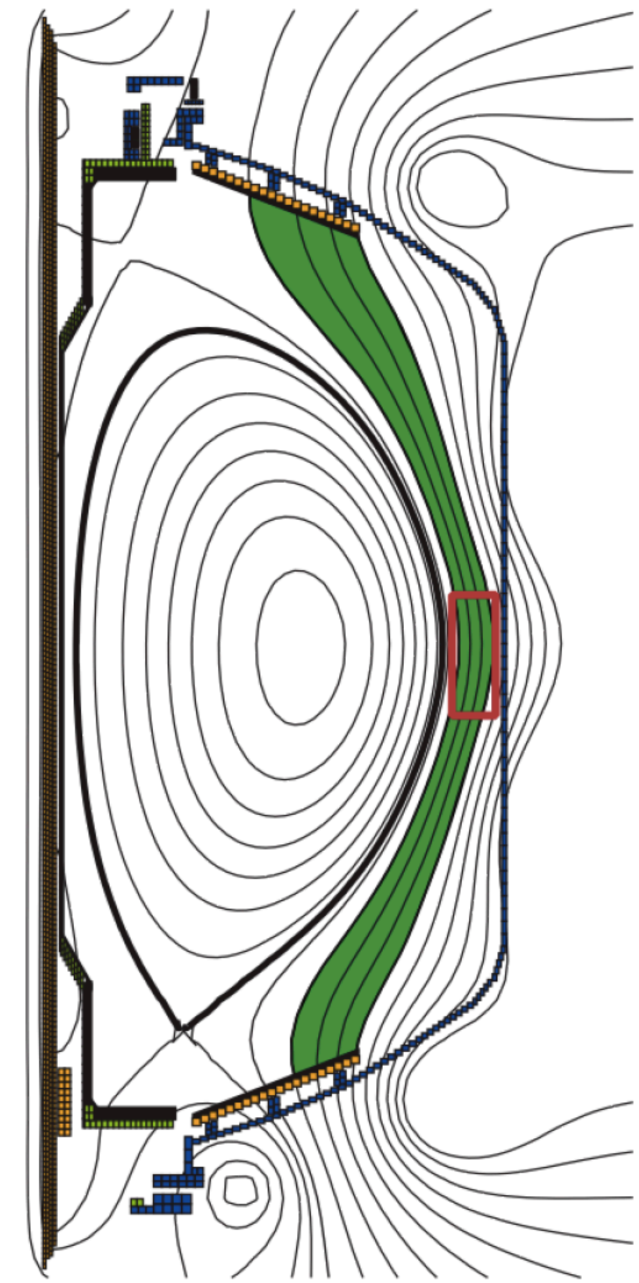
$\hat{s}$ scan: midplane profiles (EM)



- $\beta \sim 0.1\ \%$ (~ NSTX SOL)
- Profiles drop off more quickly as $|\hat{s}|$ increases
- Previous simulations with simplified geometry similar to $\hat{s} = -2$ case

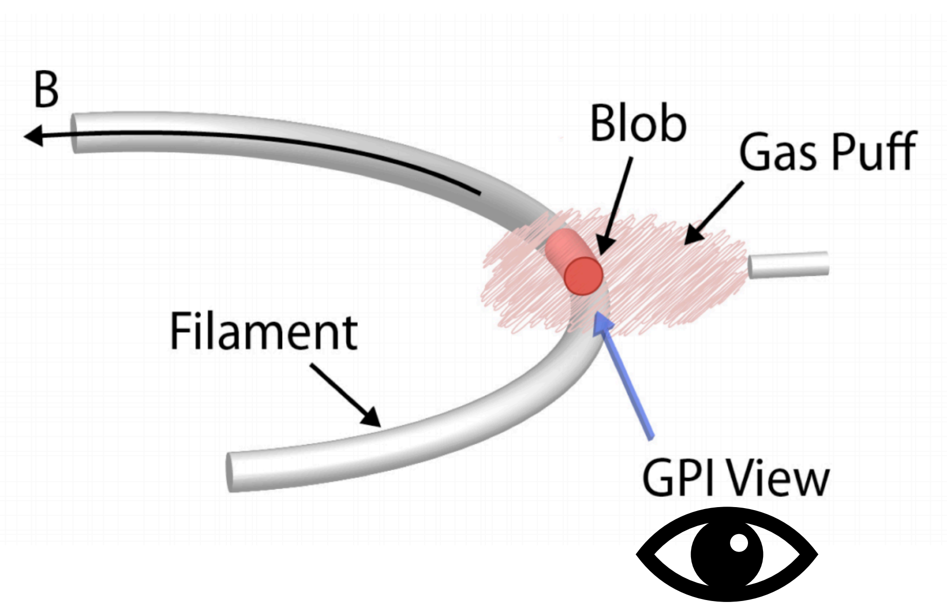
Current/Future Work

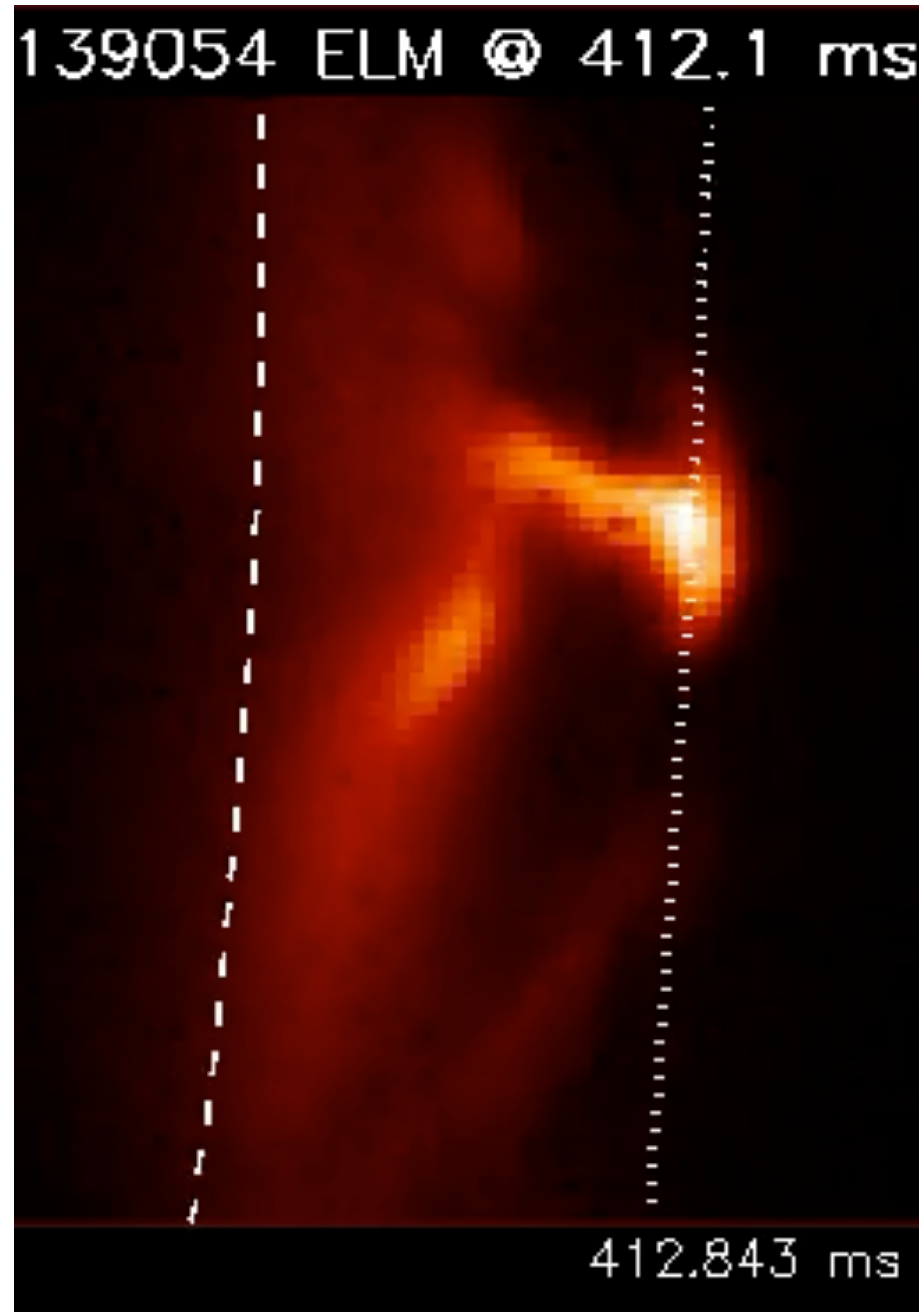
- Generalizing the magnetic geometry to include magnetic shear, non-constant curvature, closed field line regions, X-point
  - Non-orthogonal field-aligned coordinate system with magnetic shear now implemented
  - X-point is a singularity in these coordinates, challenging!
- More studies of EM effects on blobs/ELMs
  - Comparisons with magnetic fluctuation measurements in experiments?



Imaging the SOL with GPI

- GPI = Gas-puff imaging diagnostic (S. Zweben)
- Real-time turbulence movies in NSTX SOL
- Data taken using fast camera (400,000 fr/s)
- Dα intensity proportional to some combination of n and T





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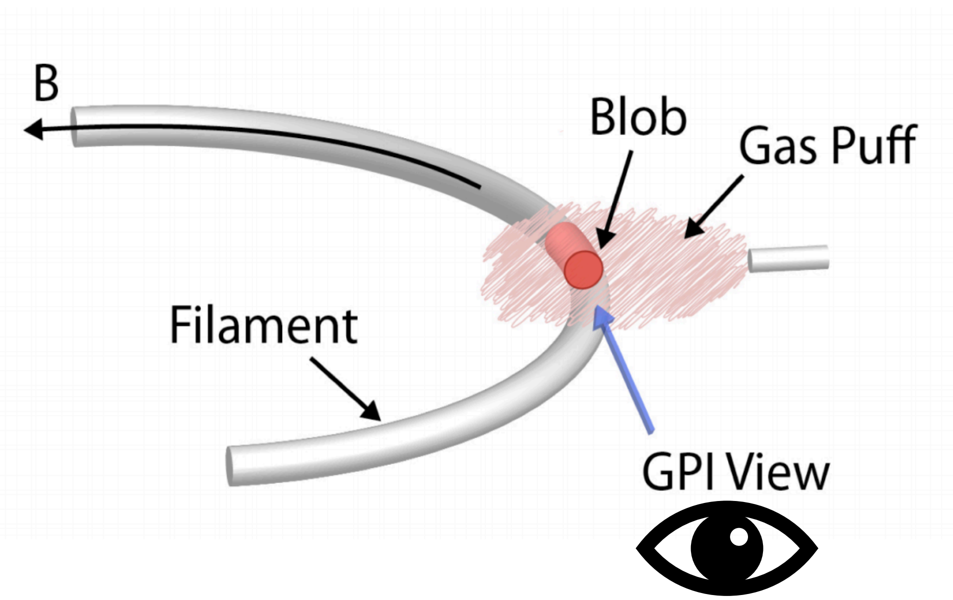
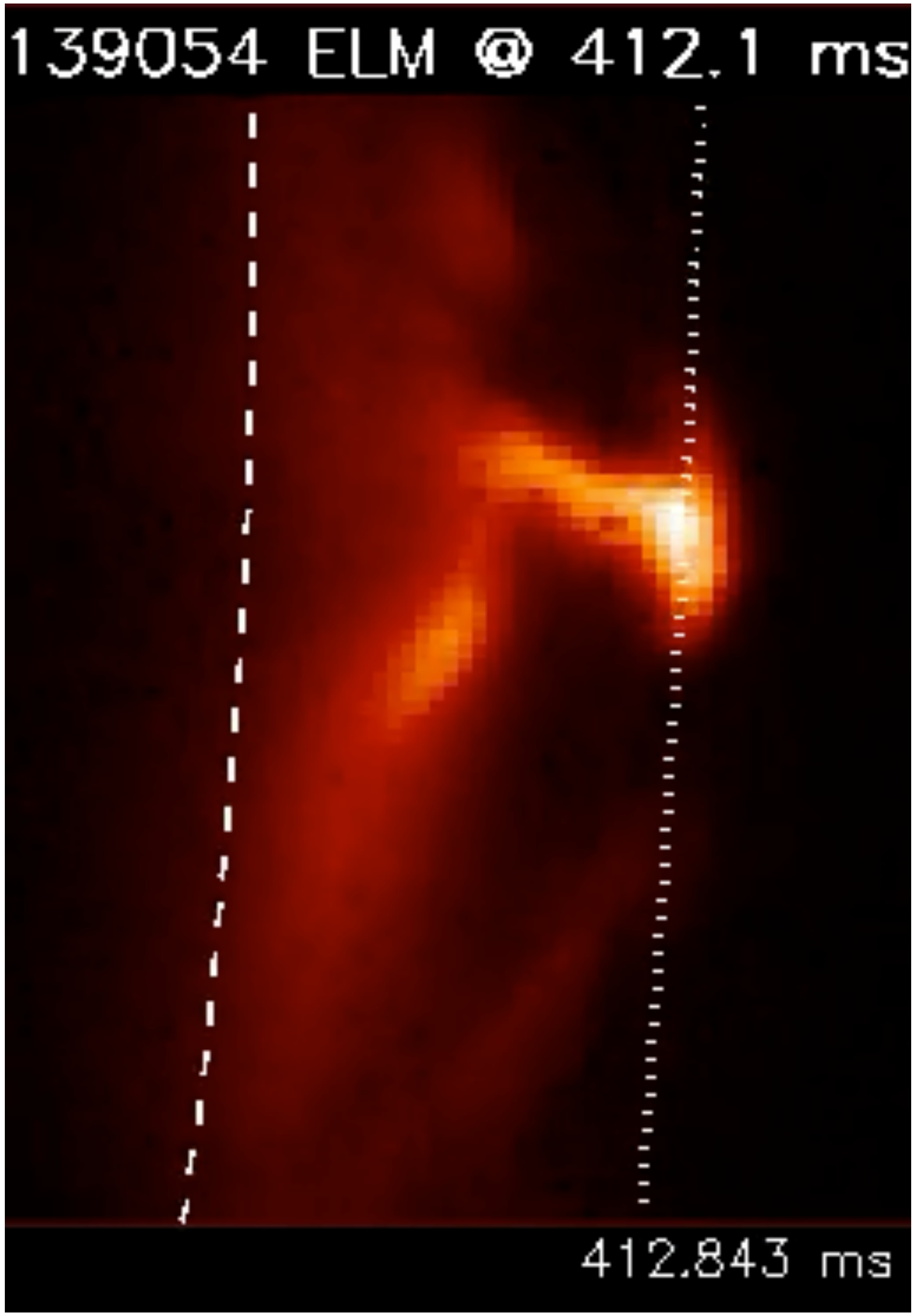
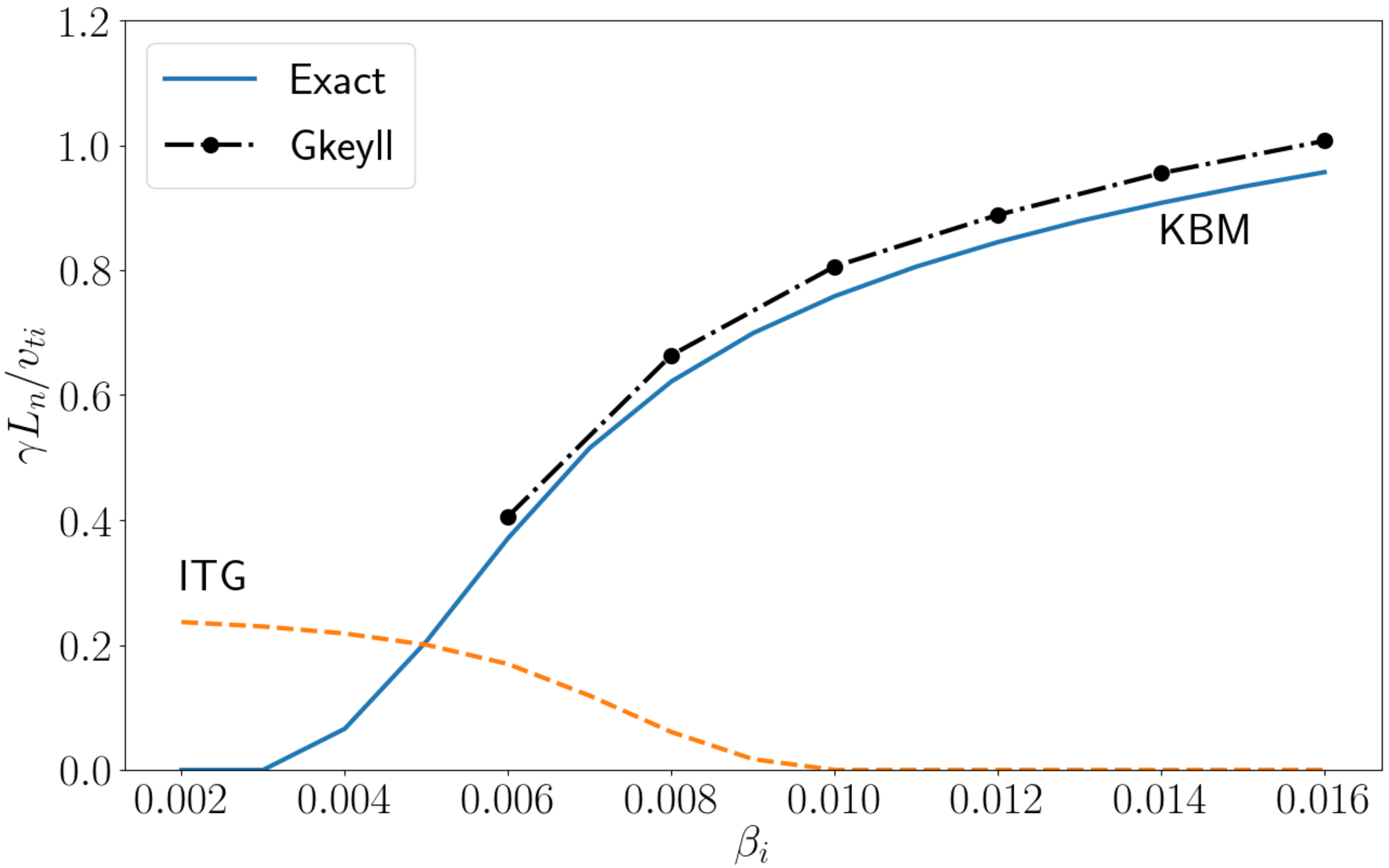




Linear benchmark: KBM instability (local limit)



$$k_\perp \rho_s = 0.5,\ k_\parallel L_n = 0.1,\ R/L_n = 5,\ R/L_{Ti} = 12.5,\ R/L_{Te} = 10,\ \tau = 1$$